The Production of Electrical Discharge Machining Electrodes Using SLS: Preliminary Results

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INTRODUCTION

Electrical discharge machining (EDM) has become common place in the tool and die industry as an alternative to conventional machining and now accounts for 2% of worldwide machining[1], with a substantially greater concentration of use in the tool making industry. EDM has the advantage of allowing tool steel billets to be heat treated to full hardness before the cavity is produced, obviating the need for heat treatment after machining--a step that often results in the loss of dimensional accuracy due to distortion in the quenching from high temperature austenite to martensite at room temperature. Any material with less than 1 ohm-m of electrical resistivity, regardless of hardness, can be machined using EDM.[1] EDM also allows the convenient production of complex shapes in the tool cavity, as complex topographies can often be more easily machined on the electrode than inside a cavity. Even certain simple shapes such as rectangular or square cavities are far easier to produce using EDM than conventional machining.

EDM machining, however, is precluded from many market niches by the relatively high cost of electrode production In visiting with approximately sixty representatives from the EDM industry, we have learned that the cost of electrode fabrication is often greater than 50%, and sometimes as great as 80%, of the total cost of fabricating a die using EDM.[2,3] The wear ratio of the two most commonly used electrode materials, graphite and copper, requires the use of multiple electrodes in the production of each cavity, because the electrode wears away and loses its initial shape too quickly. Thus, the replacement of graphite and copper electrodes with electrodes made of materials which are more resistant to electric spark erosion would significantly improve the cost effectiveness of EDM tool production.

Many tools have multiple cavities that use a different electrode for each separate cavity because it is easier to machine several small, simply-shaped electrodes than it is to machine one large, complex electrode. This requires a greater total sink time in the EDM machine, since multiple cavities are machined sequentially rather than simultaneously. The ability to create a large, complex electrode quickly would greatly reduce the time and money spent in tool production using EDM.

If the rapid prototyping technology[4-7] that has emerged during the past ten years could be utilized to fabricate EDM electrodes, the cost of producing electrodes with complex shapes could be substantially reduced, and new material systems which are difficult to machine could be utilized for the electrodes. Complex electrodes capable of making multiple imprints/cavities in dies simultaneously could be fabricated just as easily as simple electrodes using rapid prototyping equipment, which would increase the precision of the cavities' placement relative to one another, dramatically reducing the EDM machine time required. A die which might, for instance, require as many as 15 imprints, which are now done sequentially, could be done in one EDM operation, reducing the time in the EDM machine and increasing the precision of placement of the imprints relative to one another.[3] This would be a significant contribution to the tool and die industry.

Texas A&M University has undertaken research to produce EDM electrodes using rapid prototyping. Specifically, the development of a process for rapid prototyping of EDM electrodes, using selective laser sintering (SLS) of polymer coated intermetallic powders which are subsequently infiltrated with a highly conductive metal, is being investigated.

BACKGROUND INFORMATION

Rapid Prototyping

Rapid Prototyping has emerged during the past ten years as an important, new technology to facilitate rapid product development.[8] One of the major limiting factors for the application of this new technology to industry is the types of material systems current rapid prototyping machines are able to produce. New material systems and novel applications of these material systems need to be developed in order for rapid prototyping to continue to make significant inroads into the manufacturing industry.

At present, commercial rapid prototyping technologies are generally capable of making solids of polymers, paper, or ceramics used for investment casting molds.[9] However, the production of metal, ceramic and composite parts is now under development. Several approaches are being explored. First, polymer coated metal or ceramic powders may be consolidated in a SLS machine, even as polymer powders now are.[10-12] However, post processing is necessary to sinter the metal or ceramic powders and burn off a polymer "binder." The powders are coated with a very thin polymer to facilitate the initial laser sintering, since the current SLS process using the DTM Sinterstation 2000™ machine can only sinter a polymer coating on metal or ceramic powders, but not the powders themselves. Similarly, 3-D Printing could be used to consolidate metal or ceramic powders in much the same way, but post processing to burn out a binder is also necessary. Both of these techniques have been studied extensively.

Researchers at the University of Texas and elsewhere[13-15] are studying the selective laser sintering of metal and ceramic powders directly using much more powerful lasers than those commercially available in SLS machines. This approach can circumvent, at least in theory, the dimensional control problems associated with using polymer coated powders, although it presents many other challenging problems. This technology isn't commercially available and may not be for a long time.

The direct production of a material suitable for use as an EDM electrode would seem to be best done using selective laser sintering of polymer coated powders. Critical issues to be dealt with include dimensional control and surface finish, both areas which need further improvements to be generally useful for tool and die applications. Dies for metal stamping or forging will often require greater dimensional control than SLS now provides while dies for injection molding will usually need a higher quality surface finish.

Reduction of shrinkage during either SLS or subsequent sintering to a sufficiently low value, while desirable, may not be critical to the success of the project. If the process of making an intermetallic/metal electrode by SLS can be sufficiently well understood and the right variables controlled at an appropriate level, then a reproducible shrinkage, which is at least planar-isotropic and highly repeatable, could be used to compensate in the CAD program design of the electrodes such that the final parts can have a level of precision which substantially exceeds that which would be possible based on uncorrected shrinkage. DTM is able to hold tolerances of at least ± .005" on the first inch and ± .001" on every inch after that. These tolerances should improve with the advance of the technology. It should also be noted that in their development of iron/copper parts at DTM, they found that they have a better surface finish and more dimensional control in their polymer-coated iron parts than they have in their wax, polycarbonate or nylon parts. This gives us a good basis for expecting similar results in our work.

Electrical Discharge Machining

The most common electrode material for EDM in the United States is graphite. In Europe copper electrodes are the most common electrode material[2]. Specialty applications sometimes utilize tungsten/copper or graphite electrodes infiltrated with copper. These materials have a combination of electrical and thermal properties which make them particularly suited for EDM electrodes. Equally important, they are easy to machine.

For EDM electrodes, several variables are used to measure performance, including rate of sink, surface finish of the cavity produced, and spark erosion rate of the electrode compared to the workpiece, termed the wear ratio. It should be noted that behavior in these areas depends not only on the material used for the electrode but also the operating conditions as well. Thus, the comparative evaluation of various electrode materials must be done for appropriate operating conditions in the EDM machine[16-18]. It is also worth noting that the operating conditions in the EDM machine (e.g., current, pulse time, and pause time) are changed when rapid sink conditions are needed compared to final finish conditions, which are used to give dimensional control, good detail and a smooth surface finish. Thus, performance comparisons should be made for both operations.

Candidate Intermetallic/Metal Electrode Systems

The most exciting aspect of using SLS to produce EDM electrodes is the opportunity it will provide to consider materials systems which have superior performance characteristics, compared to conventional graphite and copper electrodes, but that cannot be easily machined. A combination of an intermetallic ceramic with a metal appears to be the best candidate material system.

An intermetallic with the specific characteristics of high electrical and thermal conductivity, high melting point and low, isotropic thermal expansion when combined with a lower melting-point metal with high electrical and thermal conductivity provide for the perfect combination of properties. If the intermetallic was used as an electrode, mechanical failure of the electrode would occur, without melting, by overcoming the bond strength with thermal stresses alone. This is called thermal spalling[19,20], and it occurs as the intermetallic expands and contracts during sudden temperature changes at the surface of the electrode during erosion. When a metal (usually copper) is used by itself, it erodes by melting.

When an intermetallic is combined with a lower melting point metal with excellent thermal and electrical conductivity, the combination allows for the metal to melt *and re-solidify* to the higher-melting point material (which doesn't melt), and the excess heat is carried away from the surface quickly because of the high thermal conductivity of the metal. The metal also aids in reducing the effects of thermal spalling because it is not brittle and it helps reduce the internal stresses that cause spalling.

Recent work at Texas A&M University by Gadalla & Cheng[21] has demonstrated that a composite material consisting of zirconium diboride particles surrounded by a copper matrix has superb electrode performance characteristics. The melting point of ZrB_2 is above 3300K, it has an electrical resistivity of $9.2 \times 10^{-6}\ \Omega\cdot cm$, a thermal conductivity of 24 W/(m•K) and an isotropic thermal expansion of $5.5 \times 10^{-6}/K$.[22] All of these properties seem to be ideal for the scenario just described. Copper has a melting point of 1358K, an electrical resistivity of $17 \times 10^{-7}\ \Omega\cdot cm$, a thermal conductivity of 401 W/(m•K) and a thermal expansion of $17 \times 10^{-6}/K$.

The ZrB_2/Cu composite was originally developed as 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. Proposed uses for ZrB_2/Cu based on its electrode properties include rail guns, high-current switches for pulsed power, high-power ion thrusters and arc-jet plasma reactors. These applications use a copper electrode (anode) that must be replaced frequently, which prevents continuous use due to high electrode erosion. Because ZrB_2/Cu has both electrical and thermal conductivities near those of pure copper, it can be used as a replacement electrode and would be expected to last 16 times longer than copper, according to the initial studies presented later in this paper. The main obstacle to this and many other similar applications for ZrB_2/Cu is a means of fabrication.

EXPERIMENTAL PLAN AND PROCEDURES

Electrode Fabrication Technique

The production of composite electrodes using SLS will be done in four steps. First, an intermetallic-ceramic powder is coated with an SLS-compatible polymer binder. Second, the powder is processed using a DTM SinterStation 2000™ (beta) SLS machine to "tack" together the ceramic powders by actually sintering their respective polymer coatings. This will produce the desired 3-dimensional shape of the electrode. Subsequently, a furnace annealing is used to burn off the polymer coating and sinter the intermetallic powder. Finally, the 50-70% dense network of intermetallic is infiltrated with copper.

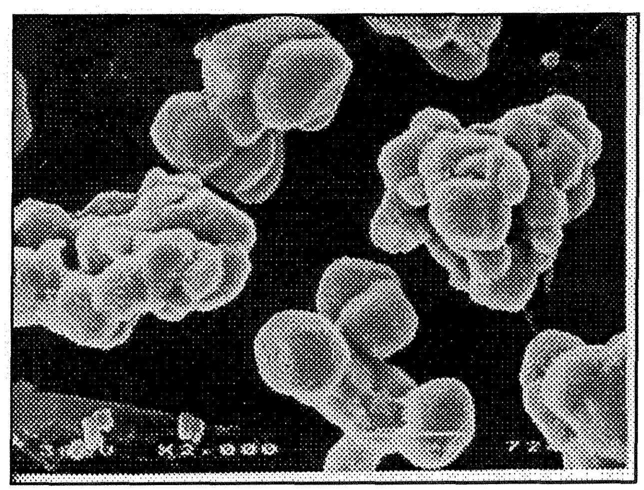

Figure 1. Polymer Coated ZrB_2 (2000X)

What is normally considered to be a liability in the SLS production of metals and ceramics, namely the lack of 100% density, is not only quite acceptable in the fabrication of EDM electrodes, but is a great asset for composite materials systems produced by infiltration. An increase in the volume fraction of metal could be produced by using SLS and post-sintering of a mixture of the metal and intermetallic powders before infiltration. Alternatively, using various particle size distributions of intermetallic powders can also be used to vary the final volume fraction of porosity before copper infiltration.

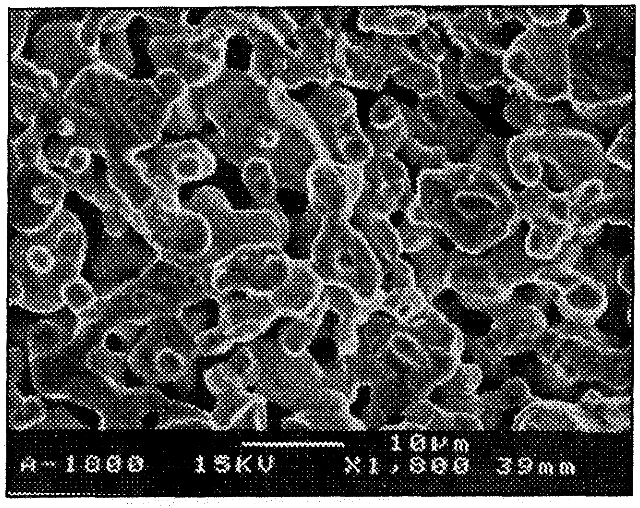

Figure 2. ZrB_2 Sintered at 1800C (1800X)

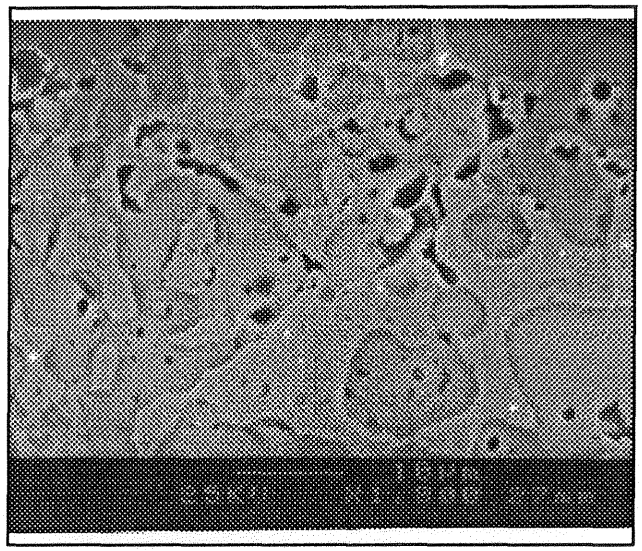

Figure 3. Infiltrated composite--black sections are voids, dark grey sections are ZrB_2 and light grey sections are copper (1800X).

Furthermore, the degree of surface roughness present with current SLS technology may also prove to be less significant in the fabrication of electrodes, since the EDM process will simultaneously erode both the work piece and the "high spots" on the electrode, potentially giving a smoothing of the electrode with use, and thus the surface finish it produces.[21]

Electrode Performance Tracking

Electrodes will be assessed at Texas A&M University and at industrial locations around the nation in order to evaluate how they perform, studying sink rate, cavity surface finish and particularly the wear ratio between the electrode and the workpiece. Interaction with these companies will help guide the research in tailoring the electrode properties to the most optimum for the manufacturing industry.

The successful completion of this research will depend on the development of a more fundamental understanding of the process of polymeric coating of metal and ceramic powders, sintering of these coatings, post SLS annealing to sinter the powders themselves, and infiltration by a lower melting point metal. The development of models to describe the relationship between (A1) polymer coating thickness and uniformity on the powders, (A2) sintering variables in the SLS machine, and (A3) subsequent thermal sintering and infiltration to (B1) dimensional control, (B2) sink rate and wear ratio, and (B3) surface finish will be an important aspect of this research. Such model development must be guided by experimental observations of the key steps in this process. Observations in the Scanning Electron Microscope (SEM), microprobe analysis, x-ray analysis, metallography, and surface analysis, among others, will be used at each step to guide in the understanding and improvement of the process and the finished electrode and it properties.

Thus, while the specific focus of this effort is on the production of intermetallic/metal EDM electrodes, the understanding developed in this investigation will not be limited to the SLS of EDM electrodes. The knowledge gained will provide generally useful information to further develop the rapid prototyping of metal and ceramic powders using the SLS process, with an emphasis on dimensional control and surface finish, the two greatest limitations in the technique at present.

PRELIMINARY RESULTS AND DISCUSSION

Assessment of ZrB_2/Cu Performance in EDM

Preliminary testing in the EDM laboratories at Texas A&M University has shown the ZrB_2/Cu composite to be far more resistant to spark erosion than any other material conductive to heat and electricity ever tested[23]. The graph in Figure 4 shows the resistance of ZrB_2/Cu to electrical erosion., where the electrode (anode) was graphite. Because of the fact that it is virtually impossible to EDM ZrB_2/Cu and that the graphite electrodes used in the attempt were themselves worn away, we felt that this material would perform well as an electrode. Initial studies have shown that, as electrodes, ZrB_2/Cu provides a rapid sink rate with an electrode wear ratio that is much less than copper or graphite, and that potentially, with an optimal microstructure and operating conditions, could be negligible.

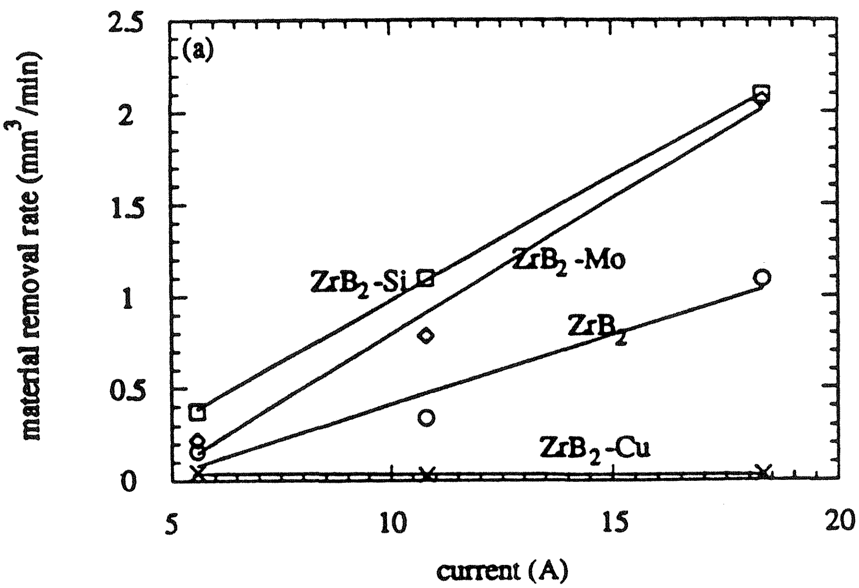

Figure 4. Material removal rate from workpiece at different currents, using a die-sinking machine (t=75μs, p=130μs)[23].

These results were confirmed by additional tests. Anodes of (1) copper, (2) graphite and (3) ZrB_2/Cu were measured for spark erosion as electrodes when machining steel in an EDM die-sinking machine. The machine operating conditions were the same for the three different electrodes: current, 63 amperes; pulse time, 18μs; pause time, 320μs. These conditions of high current and short pulse time provide unusually high electrode erosions, as was our intent for this comparison. The results in Table I show that the graphite electrode wear ratio of .150 is 4.3 times more than the ZrB_2/Cu electrode wear ratio of .0346. This agrees well with Figure 4, where Gadalla & Cheng were attempting to directly erode ZrB_2/Cu with a graphite electrode.

TABLE I.
Comparison of the Three Electrodes

ELECTRODE	Copper	Graphite	ZrB_2/Cu
Erosion Rate of Steel (mm^3/min)	3.40	4.84	3.12
Erosion Rate of Electrode (mm^3/min)	1.97	0.717	0.108
Wear Ratio (electrode/workpiece)	0.58	0.15	0.035

Table I further shows that the ZrB_2/Cu electrode has a wear ratio that is only 1/16 thatä of the copper electrode. As noted previously, this is the basis for the replacement of commercial copper electrodes in other systems besides EDM. An important thing to keep in mind when considering these results is that the ZrB_2/Cu microstructure and the operating conditions of the EDM machine were not optimized to give the best possible results for ZrB_2/Cu electrode performance. This optimization will be done during the course of our research, and it is hoped that more dramatic results will be obtained.

Sintering and Infiltration Issues

The method previously used for producing ZrB_2/Cu composites was to pre-mix the ZrB_2 and Cu powders and then press and sinter them together. This is an unacceptable method for producing parts of complex shapes. If the composite was machineable, the blocks produced in this manner could be machined in much the same way that graphite blocks are now machined into electrodes. However, since the composite is too hard to machine, the electrode fabrication technique previously described, using selective laser sintering, is necessary in order to produce useful and complex shapes. ZrB_2/Cu parts have been successfully produced using this electrode fabrication technique.

An issue of great importance for the infiltration step is wettability. Molten copper must wet the ZrB_2 particles in order for infiltration to occur. This has been a significant challenge. Oxidation and carbon contamination of the ZrB_2 on a micro scale during sintering is unavoidable, and any small amount of oxidation makes wetting by pure copper thermodynamically unfavorable, making copper infiltration impossible. In order to compensate for this problem, we have had to introduce other elements into our copper to enhance its wetting characteristics, but with a potentially negative impact on the resultant electrode wear ratio (see Figure 5). Another probable reasons for poor performance is that the conditions in the EDM machine were not optimum for the new electrode and with further tests, the results may be as good as before. Electrodes will soon be sent to EDM industrial locations around the nation for performance evaluations, which should shed considerable light on the capabilities of the electrodes produced at Texas A&M.

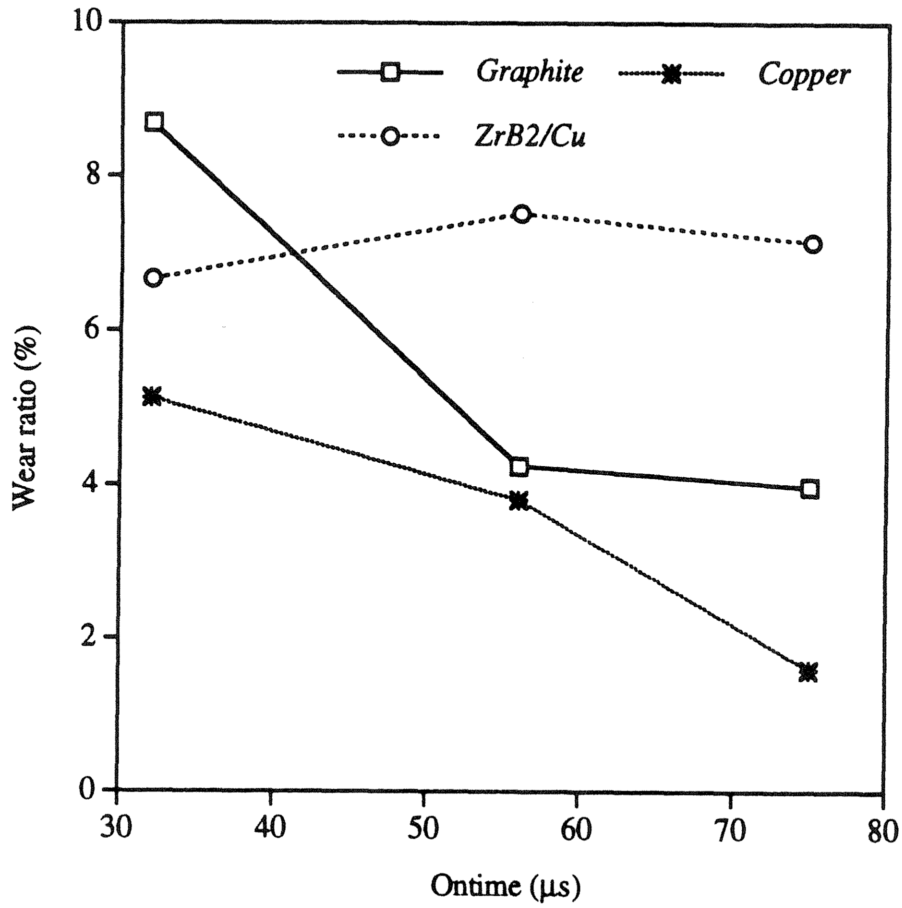

Figure 5. Wear ratio at a current of 10.8 A and off time of 130 μs.

CONCLUDING REMARKS

Industrial interest in both new electrode materials (ZrB_2/Cu) and electrode manufacturing systems (SLS) for EDM is evident. Many EDM companies have agreed to donate EDM machine time and their expertise to this project in order to assess the quality and usefulness of the electrodes produced. We have also been approached by more than 60 different companies (many of whom are smaller EDM shops and don't have the capacity to do in-house research) who have expressed interest in this research. Interaction with these companies will help guide this research in tailoring the electrode properties to the most optimum for the manufacturing industry.

Understanding how polymer coating thickness and uniformity on the powders, sintering variables in the SLS machine, and subsequent thermal sintering and infiltration affect dimensional control, surface finish, and electrode properties will be helpful not only in producing EDM electrodes with properties superior to today's standards, but will be generally useful information to further develop the rapid prototyping of metal and ceramic powders using the SLS process.

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