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Material Removal by Arc Ablation

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ABSTRACT : *Arc ablation holds the promise of fast, low-cost metal removal at faster rates than laser, plasma and electron-beam methods and without the tooling and fixturing forces of conventional machining. Preliminary results show surface finishes in the tens of microns range at high material removal rates (MRRs) by adaptive control of arc voltage: up to 97 mm3/sec at 4 kW. These results far exceed the capabilities of Plasma cutting for the same power ranges. Arc ablation can remove hardened die steels at controlled depths without dielectric baths, shield gasses or tool wear. We have also successfully cut Inconel 718 and Titanium 64. Benefit-to-risk ratios are moderate since we do not need substantially new machines for this new process. Conventional lathes and mills can be employed through insulated tooling configurations. The immediate challenges are the extension of surface ablation to hole-making and ten times the preliminary MRR: up to 1000 mm3/sec at 40 kW.*

I. INTRODUCTION:

We are motivated by high costs and long lead-times to discover new ways to deal with the manufacturing of dies for stamping and injection molding. A significant part of this cost is due to machining away relatively large volumes of hard alloy steels. A related problem exists in the manufacture of specialty aircraft parts that are machined from large blocks of titanium or high-strength aluminum alloys, leaving a small fraction of the material for actual use. In the majority of cases, sawing is not possible due to the geometry of the part, and work holding forces can limit machining process options. Common to both practices is the existence of an electrically conductive work piece. We have demonstrated removal of the great majority of this material by a fast, controlled arc ablation process. It induces melting of the work piece by electric arc in a highly localized volume and at the same time removing the melt by proximity to a rotating current-carrying tool. An examination of the energy available showed that such a process should work, and work very well. For example, the specific energy of machining alloy steel approximates the energy needed for melting: ranging from 9 to 10 J/mm^3 (less for machining softer materials). However, there is little or no force needed for work holding, no expected sensitivity to material hardness, and even a modest arc welder can supply 20 kW continuously, implying a material removal rate of 2000 mm^3/sec (at 100% efficiency). Conceptually exchanging a machining center's high-powered spindle drives for an energy-equivalent transformer widens options and increases the material removal rate (MRR) by more than an order of magnitude over present processes.

Literature Review: We have found no literature directly applicable to this new process. The extant literature concerns plasma arc cutting and fundamental constitutive relationships that have not been applied to this process at this time. In our Conclusions and Future Research section we discuss how a model could be built for this process, but this work remains in the future as our efforts continue. Commercial/Industrial processes parameters were determined for Table II, below, primarily by referencing promotional literature (web-based) and personal contacts from equipment sales representatives.

Comparison with Known, Potentially Competitive Processes: Plunge (sinker) electric discharge machining (EDM) has been developed (and in use) for decades and shown to be effective in "machining" difficult geometries with similarly low-force work holding. However, the MRRs range from only 0.02 mm^3/sec to 6 mm^3/sec, and a cumbersome dielectric bath is needed. The energy available for metal removal ranges from a few kJ to MJ systems, and the precision can be very high. [1]For comparison, we have been able to obtain a peak MRR of 97 mm^3/sec in hardened tool steel with a low-power (4 kW) preliminary test, (see Table I, below). This compares very favorably to hard turning of steel in the 0.15 mm^3/sec range. Moreover, the proposed arc ablation process is aimed at bulk material removal, not achieving finished surfaces. Therefore EDM and hard turning are not competitors to this process, either by power, efficiency or result measurements. Metal removal by other means such as gas-assisted plasma arc or laser beam, and electron beam melting is limited by a lack of depth control, and larger variations in kerf. We pre-set the depth of cut manually and the kerf is set by the width of the cutting disc used in our initial tests. As the disc moves into contact with the work piece, an arc is formed and maintained with virtually no clearance between them. For these reasons, plasma arc and laser cutting are not true competitors with a depth-controlled process. Notwithstanding these limitations, the most rapid of these processes, plasma cutting, operates at MRRs we can already achieve, as listed in Table I.

Our initial experiments (described below) show that depth can be controlled to within a tenth of a millimeter using an arc-producing disc with no “teeth” of any kind,(see Figure 1.) We measure MRR by weight change and cutting time of the test pieces. We find surface roughness with a computer-driven profilometer in our metrology lab. As we come to understand this process better, profiles of the heat-affected zone (HAZ) would be predicted based on process parameters.

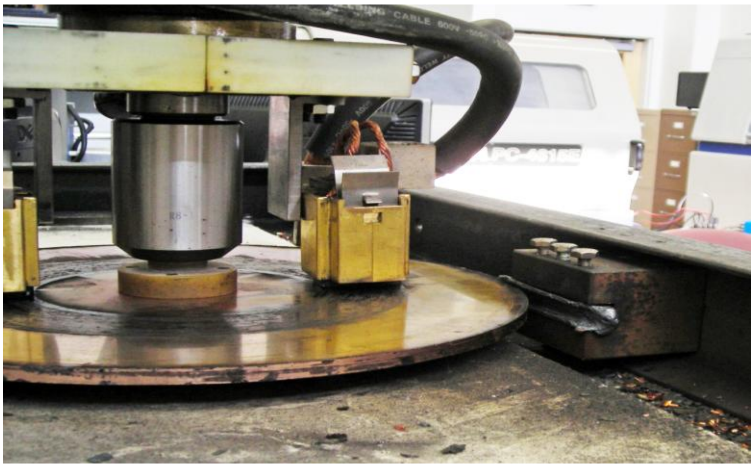

Figure 1. Experimental set-up with copper disk and high speedsteelworkpiece.

At this time, we can compare our approach to plasma cutting (100 mm^3/sec at 35 kW) and find that ablation far exceeds the MRR capabilities of representative plasma cutting for the same power ranges(100 mm^3/sec at 4 kW). Specifically, plasma cutting operates in the range of 6 W/mm^3 removed, whereas our initial experiments, not optimized, show that arc ablation operates at about 2.8 W/mm^3 removed. Moreover, plasma cutting has no depth control, but arc ablation can deliver surface finishes in the 0.1 mm range. Values for other processes listed in Table II indicate the high potential for the arc ablation process.

Table I. Preliminary Sample Results (all are for through-hardened A6 HSS)

Sample #	*Surface Speed m/sec*	*Feed mm/sec*	*Depth of Cut mm*	*MRR mm^3/sec*	*Disk Diameter mm*
1	24	12.4	0.5	50	303.9*
2	24	12.4	1.0	97	304.0
3	24	6.6	1.0	50	304.0
4	24	3.3	1.0	25	304.0
5	7.2	6.6	0.5	25	304.1
6	7.2	3.3	2.0	50	303.8
7	7.2	6.6	1.0	50	303.9
8	7.2	3.3	1.0	25	303.8
9	7.2	3.3	1.3	32	304.0
10	2.8	3.3	1.3	32	303.8

** Note that <u>no</u> significant wear has been found in preliminary testing, rather, a thin “skin” of workpiece material becomes deposited on the copper tool.*

Figure 2. Four HSS test pieces 12mm wide. Figure 3. Sample #11: grooved HSS test piece

Metal removal by milling, turning and drilling routinely require work-holding fixtures to secure a work piece due to the high thrust and normal forces created by chip-making processes. [1]Tool life in these processes remains an on-going research and development topic. [2] We have found that a relatively soft copper disc carrying a few hundred amperes shows <u>no measureable wear</u> in over fifty ablated work pieces such as those shown in Figure 2. The copper disc develops a thin skin (0.1 to 0.3 mm) of work piece material immediately after the arc starts. During these initial experiments this disc removed 50,000 mm^3 of hardened A6 tool steel, 10,000 mm^3 of Ti6Al4V alloy and a similar amount of Inconel 718 with negligible measured wear (less than 100 microns).

<u>Table II. Comparison of Capabilities for Selected Processes</u>

	MRR Range mm^3/sec	Spec. Power W/mm^3	Surface Finish microns (µm)	Depth Control
Arc Ablation	25 – 97	2.8	10-100	yes
Laser Cutting	0.5 – 5	1100	6 – 10	no
Plasma Cutting	10-100	9.2	4 – 10	no
EDM	0.2 – 6 [4]	36	0.5 – 5 [4]	yes
E-beam	0.1 – 0.2 [4]	3750	1 – 6	no

We have performed a two-pronged approach to finding practical values and limits to a laboratory-based arc ablation process: *process control* of the mechanical and electrical parameters, and *design* of experiments with measurement of the process parameters.

Process Control: Our initial studies have been carried out in two steps: (i) by setting the feed, speed and depth of cut for test specimens, and (ii) by setting the preceding three parameters and the maximum current available to the process from a conventional arc welder (DC+, DC-, or AC). We have observed the state of the arc present under a wide choice of factors. We have also improved upon this approach by developing an algorithm that adaptively controls mechanical parameters for arc creation and stabilization. Initial trials have shown that both depth of cut and feed rates affect arc voltage, and hence the appearance of the arc and its effects on the test specimens. Specifically, a stable arc results in the familiar sound of a properly formed arc for welding with minimum spatter and maximum penetration depth. Through various trials we have found that such an arc can be formed and maintained by employing a real-time measurement of the arc voltage. (Figure 3) This voltage measurement is then used to control the relationship between depth of cut and feed rates. Using this technique for adaptively controlling the arc voltage, we have observed that the surface finish can be maintained, and that MRRs can be increased well beyond the 100 mm^3/sec rate found in the tests for which results are reported in Table I at higher applied power levels. The experimental protocol provides additional quantitative results. At present, we find it impractical to control weld current directly, however, the addition of a high-frequency "adapter" is expected to take care of this issue. A comparison of values of material parameters, listed below in Table III, clearly shows that the thermal and mechanical properties of our subject materials vary widely compared with those of hardened tool steel, our "reference" material.

Table III. Target Material Properties Comparison

Property Material	C_p J/g-C	k W/m-K	T_m ºC	UTS MPa	Res. -m
Ti64	0.53	6.7	1630	950	1.7E-6
Inconel 718	0.43	11.4	1300	1375	1.4E-6
Hardened A6	0.46	26.0	1600	2100	3.0E-6

Here, C_p is the specific heat, k the thermal conductivity, T_m the melting temperature, UTS the ultimate tensile strength, and Res. the electric resistance. The wide disparity in these values would affect welder current and voltage for the arc ablation process to be an effective technique for removing material. A schematic sketch of the test set-up problem is shown in Fig. 2.

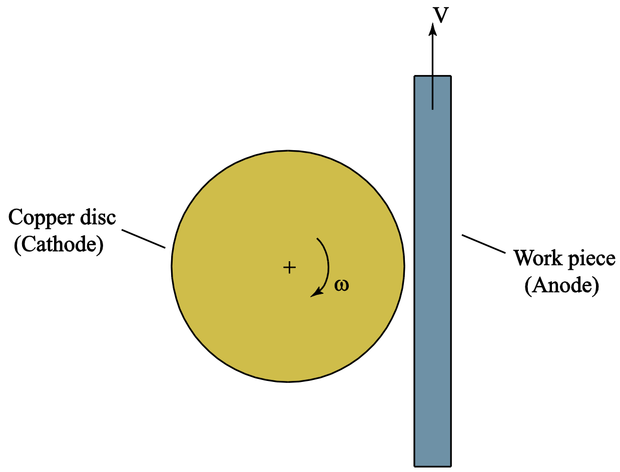

Fig. 2 Schematic sketch of the arc ablation process for developing a process model

III. DESIGN OF EXPERIMENTS

Preliminary Performance Testing has been carried out. Further experimental hardware testing is planned to be fractional factorial, since a large number of factors (and their potential interactions) are envisioned. We have performed a conservative 3-factor array performed on ten repetitions for statistical significance, (3x3x3x10 experiments).The results confirm the initial tests of Table I. Our Selected Materials List comprised mild steel (e.g., 1020), tool steel (e.g., through-hardened A6), Inconel 718, and high-strength titanium (e.g., Ti-6Al-4V). These are chosen for their popularity in many industrial manufacturing, aircraft and military applications. Our Parameter List comprises surface speed, current, width of cut, depth of cut, feed rate, mode of tool motion (continuous, “peck cycling”, adaptive voltage-controlled, varying depth), and MRR. Using MRR as the desired output parameter, we find far more factorial parameters than can reasonably be investigated exhaustively. Therefore, for each one of the four materials, we began by finding the most sensitive 3 factors of that parameter list and performed a full factorial experimental protocol on them.

IV. RESULTS:

The factorial experiments were performed in lieu of predictions and validations since at this time there is very little known about arc stabilization in air and the fluid dynamics of the ablation process. The factorial experiments controlled feed and speed of the cutting/grooving disc and held depth of cut constant at 2 mm. Feed rates of 30, 50 and 70 mm/second were controlled. Surface speeds of the disc were set to 2300, 4300, and 7600 mm/second. We recorded current, voltage and time resulting in 27 graphs, as representative of which is shown in Figure 3. The only anomalies found were an occasional loss of the arc (and concurrent drop in voltage), and it remains to determine the cause of these.

Concept Geometry: For the initial processes of grooving, a current-carrying copper disc was mounted to the spindle of a conventional milling machine. A set of copper/graphite electrical brushes were also mounted to the mill gear head. A steel working tray with safety guarding was connected to the negative post of a DC arc welder, while the brushes were connected to the positive post. (Figure 1). Reversing the polarity had no apparent effect on the arc formation or the ability to remove metal from an HSS work piece.

In contrast, we find that grooving Ti-64 is best accomplished with an AC arc setting, but that surface finishes are poor by comparison to EDM as shown in Table III, above. The process of surface finishing has not yet been attempted, but the proposed geometry would mimic face milling. In this case, we would be finding the limits of surface speed, depth of cut and feed rate. Similarly, hole-making remains to be tried and characterized. Its geometry would be determined as a result of the lessons learned in the prior experiments, but we conjecture at this early stage that a tool shaped very much like a conventional fluted milling cutter would be employed to lift and remove the melt at high velocity. Preliminary observations show that the melt would remain liquid for several milliseconds and be cleanly removed as frozen particles thereafter.

Observation methods: Our method for gaining a qualitative sense for the process of removing material by arc ablation included collection of the offal. The spray of material issuing from the ejection area at the meeting of the disc to the work piece was found to be very quickly frozen with very little incandescence (in steel), and little evidence of the liquid state. We also examined the approximate volume of material left behind on the work piece and on the disc itself. The material left on a typical work piece was negligibly small (less than 1%) compared with the total volume removed, except at the exit end, which often had the form of a frozen droplet a few mm in diameter. This result shows that better voltage control of the process is needed. The corresponding material deposited on the disc was measured to be as little as a few percent to as great as 60 mm^3, or 10% of the ablated material. Observation of Ti-64 indicated that incandescence was longer-lived and that surfaces were rougher. It remains to determine the causes of these phenomena. During each experimental cut with adaptive control, electrical data was collected. It was found that power was relatively constant at about 4 kW for our peak current experiments as shown in Figure 3. This figure represents one of many that show a slight decline in power over time for Ti-64 work pieces. We conjecture that the overall temperature of the work piece was steadily rising during the experiment. This could be validated with the addition of thermocouples imbedded in the work piece holder and temperature modeling.

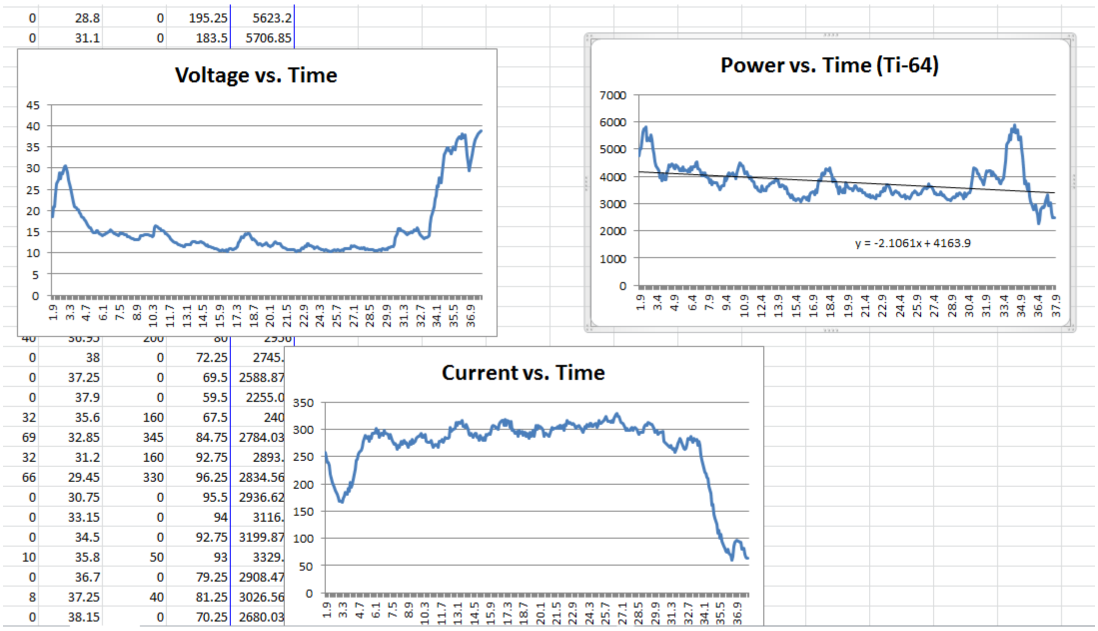

Figure 3. Electrical Measurements during a Ti-64 Grooving Experiment.
NB: The 1st graph shows Volts vs seconds, the 2nd shows Watts vs seconds,
the 3rd shows Amperes vs seconds.

The sharp and brief rise in power at the end of the work piece was almost always seen in conjunction with an increased brightness of the arc as the disc "cleared" the work piece. This result suggests that better voltage control is needed to modulate the exit temperature of the process. Just as handbook values for these parameters have been found through experiment and theoretical characterization for existing machining processes, we are demonstrating controlled ablation over a range of "cutting" conditions. Concurrently, the loss of tool volume would be correlated with those parameters that induce wear, which in turn, produce differences in surface quality and net energy cost per mm^3 of material removed.

V. CONCLUSION AND FUTURE RESEARCH:

Our principal aim has been to model and demonstrate metal arc ablation such that it becomes far superior to rough machining. A secondary aim is to show that turning, milling and drilling can all be accomplished with a lower force and energy with the arc ablative process than that with machining. Specific energies of various materials have long been known to predict overall MRRs and process energy requirements. These would be quantitatively compared to the virtually force-free but higher temperature controlled arc created during ablation, producing a new measure of efficiency. The arc ablation process would also be exploited in multi-axis milling and lathe turning in which grooving, surface finishing, hole-making and turning are characterized, respectively. This will enable us to delineate whether the same set of parameters provide optimum MRRs under different loading conditions. We have not determined the ranges of cutting parameters at this time. It is also clear to us that a coupled electro-thermo-mechanical model will be needed to begin to understand and fully exploit this process.

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