1. Introduction to Arc Ablation

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 envision removal of the great majority of this material by a fast, controlled arc ablation process. It would induce 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 shows 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 should widen options and increase the MRR by more than an order of magnitude over present processes.

Realizing that optimizing a process through tests is very expensive, we propose building up an experimental and computational science-base for controlled arc ablation, such that tool design, feeds, speeds, and overall energy usage (including current and time) would be determined for target alloys. Just as handbook values for these parameters have been found through experiment and theoretical characterization for existing machining processes, we propose to demonstrate 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.

2. 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. As the disc moves into contact with the workpiece, 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, and 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. 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.

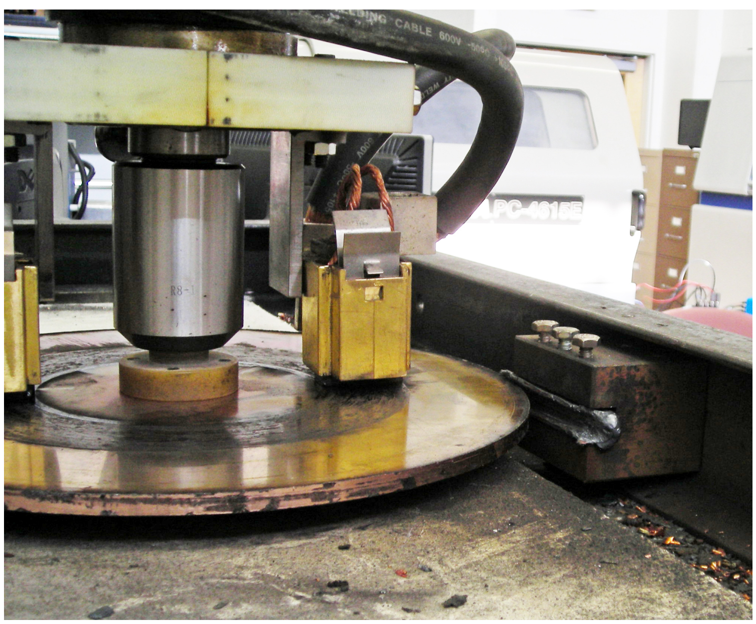

Figure 1. Experimental set-up with copper disk and high speed steel work piece.

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.

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 no significant wear has been found in preliminary testing, rather, a thin "skin" of work piece material becomes deposited on the copper tool.*

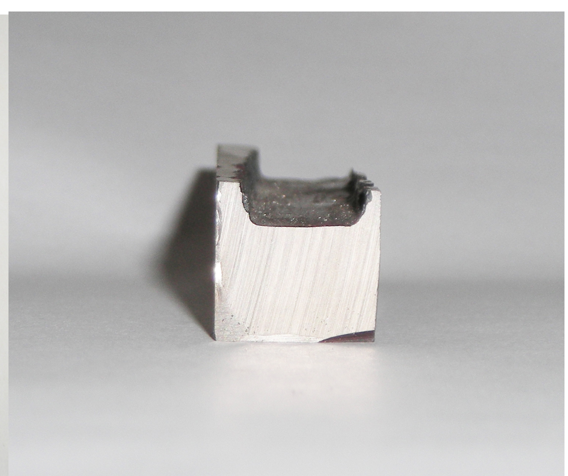

Figure 2. Four HSS test pieces 12mm wide. Figure 3. Sample #11: grooved HSS test piece

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. 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 no measureable wear 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 workpiece 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 (also commonly called Ti-64) and a similar amount of Inconel 718 with negligible measured wear (less than 100 microns).

Table II shows in brief the quantitative results of comparing Arc Ablation with common industrial processes.

Table II. Comparison of Capabilities for Selected Processes

	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[33]	1100[9]	6 – 10[5]	no[9]
Plasma Cutting	10-100[6]	9.2[31]	4 – 10[6]	no[7]
EDM	0.2 – 6[27]	36[10]	0.5 – 5[28]	yes[30]
E-beam	0.1 – 0.2[27]	3750[32]	1 – 6[5]	no[8]

**Initial Experiments Only*

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	C_p J/g-C	k W/m-K	T_m ºC	UTS MPa	Res. Ω-m
Material					
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. We plan to develop mathematical and computational models described below.

A schematic sketch of the process model is shown in Fig. 4. The mathematical model of the process will be developed in the following three stages.

Stage 1: the two electrodes, namely the cathode (copper disc) and the anode (work piece) are stationary.
Stage 2: the work piece has a uniform translational velocity.
Stage 3: the cathode is rotating at a uniform angular velocity and the work piece is translating with a uniform speed.

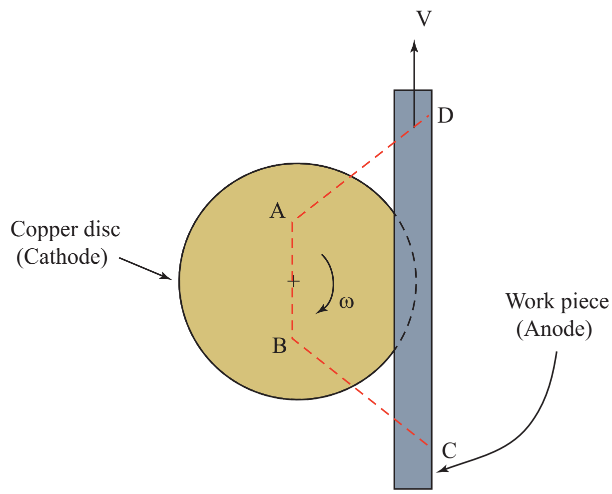

Fig. 4 Schematic sketch of the arc ablation process for developing a mathematical model. The computational domain ABCD is fixed in space, and material flows through it.

3. Preliminary Results

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 gearhead. 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.

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. This phenomenon will be explored thoroughly, since it essentially alters the boundary conditions of arc ablation. 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 5. 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. The temperature rise and its distribution in the specimen would be found by either using thermocouples attached to the workpiece or suitably placed infra-red cameras.

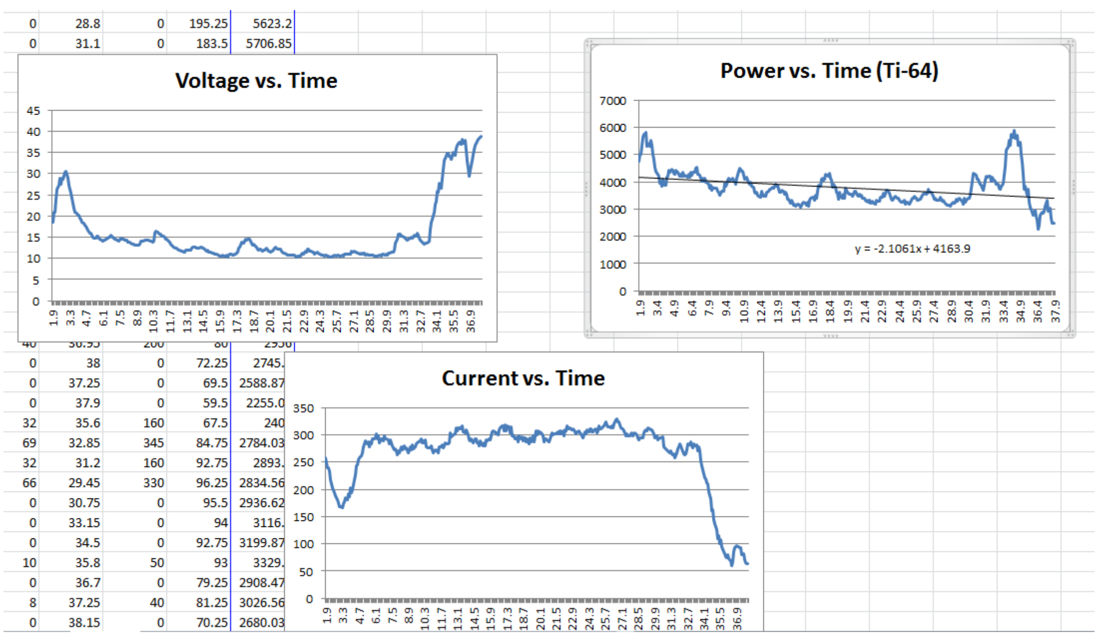

Figure 5. Electrical Measurements during a Ti-64 Grooving Experiment.