BATCH MODE MICRO-EDM FOR HIGH-DENSITY AND HIGH-THROUGHPUT MICROMACHINING

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ABSTRACT

This paper examines scaling issues for electrode arrays used in micro-electro-discharge machining (micro-EDM). In particular, it explores constraints in the fabrication and usage of high aspect ratio LIGA-fabricated electrode arrays, as well as the limits imposed by the pulse discharge circuits on machining rates. A LIGA-fabricated array of 400 Cu electrodes with 20 μm diameter was used to machine through-holes in 50 μm thick stainless steel. An array of multi-layer structures that included tapered shapes was fabricated by the sequential use of three electrode arrays of varying shape. The electrode fabrication and usage for these efforts are described. With respect to the pulse discharge circuits, it is shown that the machining time can be reduced by >50% by dividing the electrode array into sections have independent control of pulse discharge timing. This is implemented by using individual RC timing circuits for each section. A correlation between electrode area per RC circuit and machining rate is described.

I. INTRODUCTION

Micro-electro-discharge machining (micro-EDM) is a technique in which machining of conductive materials is implemented by sequential electrical discharge pulses generated between a microscopic electrode and a sample while both are immersed in a dielectric oil [1]. This technique is very attractive because it can be used for materials as varied as steel, graphite, and even permanent magnets. It has been commercially used for applications such as ink-jet nozzle fabrication. However, traditional micro-EDM is limited in throughput because it is a serial process which uses a single electrode. The use of a single electrode limits not only the throughput but also precision because the electrodes themselves are individually shaped by micro-EDM, and some variation in the electrode shape may exist.

Recent work has demonstrated that the constraints on precision and throughput can be circumvented by using lithographically fabricated LIGA-based electrode arrays as illustrated in Fig. 1. In the studies reported in [2, 3], 4x3 arrays of electrodes with height-to-width aspect ratios of 3 were fabricated from electroplated Cu and used to machine perforations in stainless steel workpieces. As a continuation of these efforts, this paper reports on scaling limits for the electrode shape and array size. In particular, it explores (i) the size and shape limits imposed by the fabrication and the usage of the electrode arrays, and (ii) the throughput limits imposed by the pulse discharge circuits.

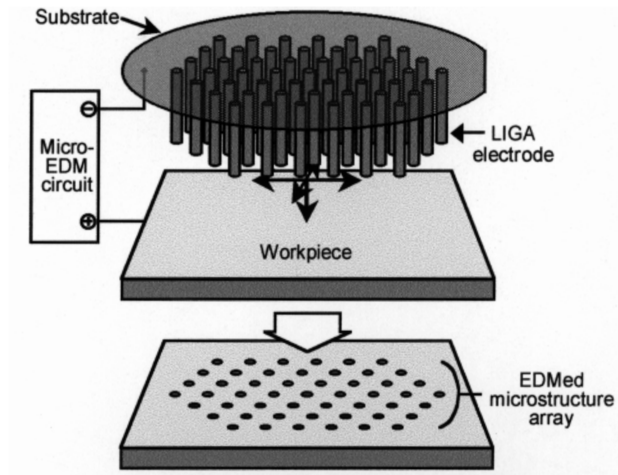

Fig.1: Concept of batch mode micro-EDM.

II. ELECTRODE FABRICATION & USAGE

Figure 2 shows a 20x20 array of electrodes with 20 μm diameter and 60 μm pitch. The electrodes have 300 μm structural height were fabricated from electroplated Cu on a Si substrate using LIGA technology. This array represents a 30x increase in electrode count and 70x increase in spatial density over past efforts [2]. In conventional EDM, the workpiece is held stationary in a horizontal position, while

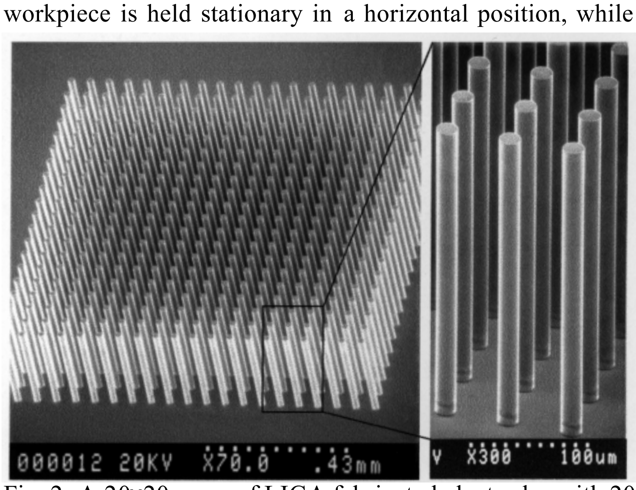

Fig. 2: A 20x20 array of LIGA fabricated electrodes with 20 μm diameter and 300 μm height.

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a single cylindrical electrode is scanned across its surface. The electrode is simultaneously rotated at 3,000 rpm in order to increase uniformity and prevent local welding to the workpiece. This rotation is clearly not possible when using arrayed electrodes. Instead, the electrodes are placed on a vibrator that dithers them along the axis of approach. The workpiece is scanned across the probe array in this arrangement.

Using the electrodes shown in Fig. 2, an array of 400 through-holes was successfully produced in 50 µm thick stainless steel by experimental apparatus based on the Panasonic™ MG-ED72W micro-EDM machine (Fig 3a). The machining time was ≈5 minutes, which is 20x-30x less than that required for serial machining by a single electrode.

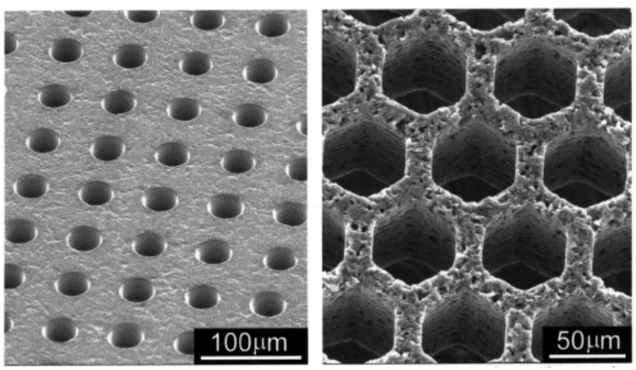

Fig. 3: (a-left) Perforation of stainless steel using electrodes of Fig. 2. (b-right) Graphite honeycomb structure formed by array of hexagonal electrodes.

Figure 4 shows the variation of hole diameters along a diagonal of the 20x20 array. The difference between the typical perforation diameter of 30-32 µm and the electrode diameter of 20 µm suggests that the lateral discharge gap is 5-6 µm. This is relatively large compared to the 2-3 µm gap that can be achieved by rotating single electrodes under comparable operating conditions. The enlargement of the hole is believed to be caused by debris from the discharge process, which includes particles removed from the workpiece and electrode as well as carbon residue from the dielectric oil. The debris are flushed away more effectively by rotating the electrode than by dithering it. The secondary discharges that occur between charged debris and workpiece are likely to enlarge the discharge gap. Figure 4 shows that the holes in the center of the array are larger than those at the periphery. This is consistent with the hypothesis of debris removal.

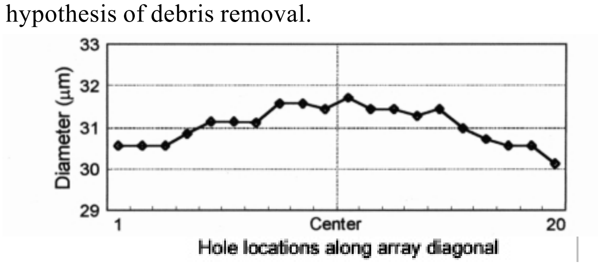

Fig. 4: Variation of perforation diameter in an array.

Figure 3b shows a honeycomb structure fabricated in 125 µm thick graphite by using arrayed electrodes with hexagonal pattern shape. The pitch of hexagonal cells is 70 µm and wall thickness is 16 µm. Since graphite has high thermal conductivity, such structures may be suitable for heat exchange applications.

Figure 5 shows microchannels fabricated by the sequential application of arrayed electrodes of three different shapes, each of which contributes to a structural "layer". The layer-to-layer alignment accuracy of 0.1 µm is afforded by the precision of the workpiece movement in the micro-EDM and the tight dimensional tolerance of LIGA. Note that each through-hole in the figure has a 40º taper at the top. This was created by a scrolling motion of electrode array. Figure 5 demonstrates that the combination of LIGA electrodes and micro-EDM can be used to create shapes that neither may achieve individually.

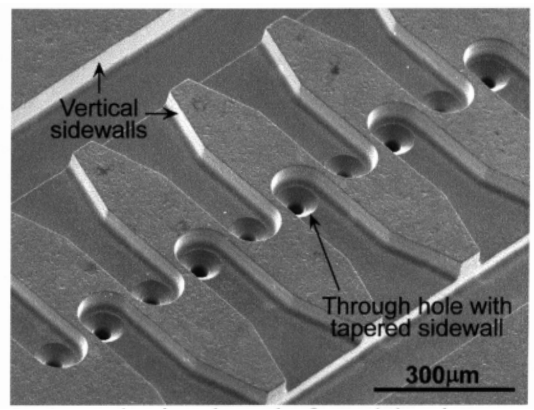

Fig. 5: Arrayed microchannels formed by the sequential application of three different electrode arrays.

The scaling limits for batch mode micro-EDM are related to both electrode fabrication and the micro-EDM process. The lower limit on electrode diameter is constrained by the plating process because of the height of the electrodes and the relatively small footprint. Figure 6 shows void formation and adhesion problems in 10 µm wide, 300 µm tall electrodes at the end of the LIGA fabrication process. Adhesion failure may additionally occur during the micro-EDM process on rare occasions.

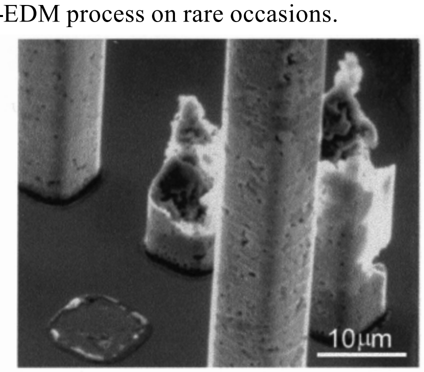

Fig. 6: Defects in Cu plating for 10 µm wide, 300 µm tall electrodes.

Other problems observed in using high aspect ratio, densely packed electrode arrays include the following. The debris produced during the machining process gradually form lumps that tend to clog dense arrays or complex shapes. This problem is exacerbated in the context of lithographically fabricated electrode arrays because the debris are trapped between the workpiece and the electrode substrate. Trapped debris increase the likelihood of irregular arcing that disrupts regular discharge pulses. They may also deform the electrodes. Another concern is that arrays of narrow electrodes have an increased potential for damage from local pressure fluctuations (shock waves) that will be created in the dielectric oil as it is heated by discharge pulses.

III. PULSE DISCHARGE CIRCUITS

As the number of electrodes in an array increases, in order to obtain the highest machining rate it is necessary to sustain the discharge pulse frequency as well as to permit independence in the pulse timing at each electrode. For high-throughput machining with high precision, very small and well-controlled discharges should be generated by individual circuits connected to electrically isolated electrodes. As a first step, to observe the effect of the parallel discharge mode, the electrode arrays were partitioned into four sections that were connected to separate micro-EDM circuits as shown in Fig. 7. Each partition had two 200 μm diameter electrodes connected to one circuit through the plating base. Figure 8 shows experimental setup of the partitioned electrodes. Each RC pair consisted of a 1 Kohm resistance and 100 pF capacitance. The stainless steel workpiece served as a common anode, whereas the separated electrodes served as cathodes. The supply voltage was 80 V.

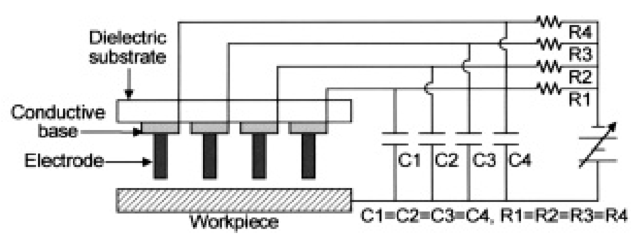

Fig. 7: Experimental setup for generating parallel discharges.

The effect of changing the partitioning of RC circuits is studied by its impact on the time required to machine a fixed depth. In order to evaluate the measured times, it is important to note the following aspect about the operation of the micro-EDM apparatus. In order to sustain discharges with a fixed gap between the workpiece surface and the electrode tips, the electrodes must be advanced along the axis of approach as the workpiece and electrodes are eroded. If the electrodes are advanced with a rate that exceeds the erosion rate, they will come into contact with the workpiece, leading to a short circuit that can be detected by the apparatus. The equipment is designed to automatically retract the electrodes if this occurs. Consequently, the user-programmed value of the electrode advance rate should not significantly affect the actual machining rate as long as it exceeds the maximum machining rate achievable by the other operating conditions. This was experimentally verified by dithered operation using single and arrayed electrodes. A programmed value of 8 μm/s, which satisfied this lower bound, was used in the following experiments.

The electrodes of Fig. 8 were advanced up to 100 μm depth in stainless steel workpieces under three different configurations of the RC circuit. Figure 9 shows a comparison of machining times in each case: "1 circuit" denotes the connection of a single RC pair (with the values provided above) to all four electrode partitions in parallel; "2 circuits" denotes two RC pairs, each to two partitions in parallel; and "4 circuits" denotes the use of a separate RC pair for each partition. It was found that the machining time for the last was less than half that of the first.

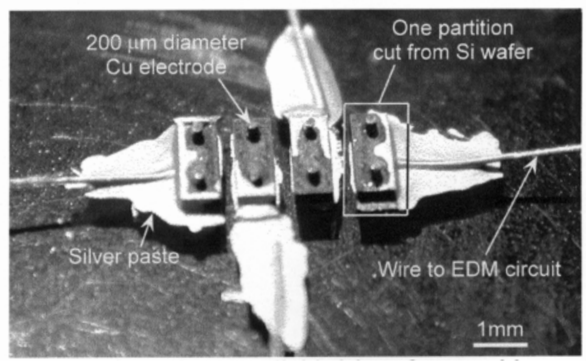

Fig. 8: An electrode array divided into four partitions with individual leads.

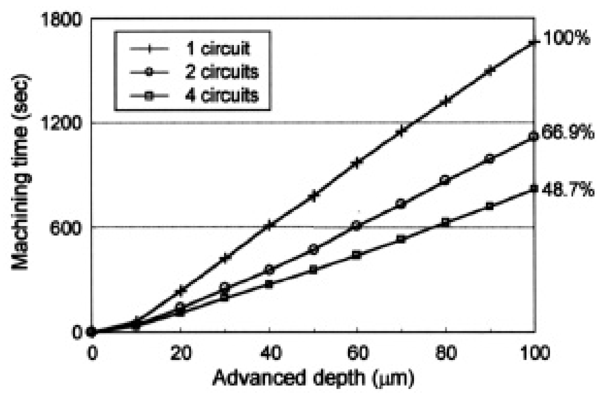

Fig. 9: Machining time for 100 μm depth in stainless steel using the electrodes of Fig. 8 with 1, 2, and 4 RC pairs.

Figure 10 shows the timing diagram for the discharge pulses of two partitioned electrodes. The measurements were taken with current probes, which have a minimal loading on the discharge circuits. It is evident that when an RC pair is shared between two electrodes, only one electrode may fire at any given moment. The electrode which is closer to the workpiece surface will tend to dominate,

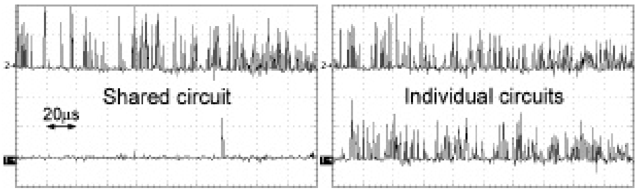

Fig. 10: Timing diagrams showing discharge pulses for two electrode partitions (a-left) sharing one RC circuit, and (b-right) with separate RC circuits.

effectively alternating the operation between the shared partitions. In contrast, when individual RC pairs are used for each partition, both can be firing all the time, resulting in a faster machining rate.

In Fig. 9, the time savings are shown to be not in direct proportion to the number of RC pairs used. Since the RC pair determines the total power available through the electrode for a given supply voltage, it is worthwhile to evaluate the impact of electrode area served by one RC pair on the machining rate. Figure 11 compares the machining times required for 100 µm depth in a stainless steel workpiece using single electrodes of varying cross-sectional area served by a single RC pair with the data of Fig. 9. Similar machining conditions were used in both cases. It is evident that for both single and arrayed electrodes, there is a linear dependence between the machining time and the electrode area served by an RC circuit pair. However, the latter results in a time-axis intercept of about 500 sec., suggesting that for arrayed electrodes, there is a point of diminishing returns beyond which the machining rate may not be increased by adding RC pairs to the discharge circuit. This effect is further analyzed in Fig. 12. Two hypothetical cases are evaluated in this figure, using the trend shown for arrayed electrodes in Fig. 11, and assuming that it will be sustained as the net electrode area is increased. In one case, the array consists of 200 electrodes of 200 µm diameter, whereas in the other case only 20 electrodes are present, resulting in 10x smaller area. The plots show the machining rate (normalized to that achieved with a single RC pair) increases with the number on RC partitions more effectively for large areas.

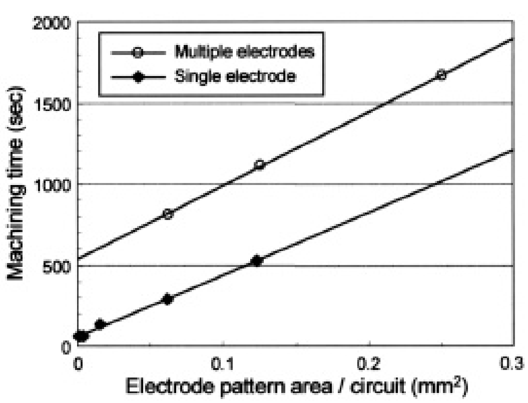

Fig. 11: Variation of machining time for 100 µm depth as electrode area per circuit is increased.

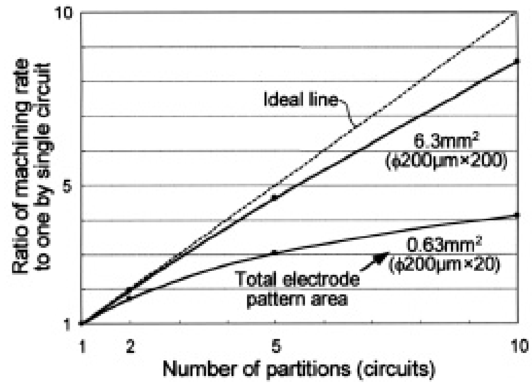

Fig. 12: Projected increase in machining rate as number of partitions is increased.

IV. CONCLUSION

This effort has explored scaling issues in the fabrication and use of LIGA-fabricated electrode arrays for batch mode micro-EDM. Arrays of up to 400 electrode elements with 20 µm diameter and 300 µm height were fabricated from plated Cu using LIGA technology. Further reductions in electrode diameter may be possible if void formation in the plating process can be eliminated. The fabricated arrays were used to machine stainless steel and graphite samples. The variation of hole diameter across the electrode array was studied. The impact of partitioning the array and using separate discharge timing circuits for each partition was also examined. A linear relationship was found to exist between the machining time for a target depth and the electrode pattern area per circuit. The experimental results were extrapolated to predict the potential improvement in machining rate afforded by increasing the number of partitions. The results suggest that the machining rate can be increased by a factor of 4-8 if 10 partitions are used in electrodes of 0.6-6 mm^2 area. These results are very promising for further improvements in the throughput of micro-EDM, and will be pursued in future efforts.

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