High-aspect-ratio WC-Co microstructure produced by the combination of LIGA and micro-EDM

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Abstract A high-aspect-ratio WC-Co (tungsten carbide super hard alloy) microstructure has been produced by a new microfabrication process which combines LIGA and micro-EDM (electro-discharge machining). The 1 mm long microstructure with gear pattern has a variation of 4 μm in the outside diameter along its length. In the process, LIGA fabricated electrodes of negative geometry are electroplated in a metal plate for use in the micro-EDM. Since the arrangement is extremely precise the serial micro-EDM processes for one workpiece can be implemented by exchanging worn electrodes for new ones via X–Y positioning between the workpiece and each electrode. In this type of machining any bulk conductor can be chosen as the material, which is to be shaped into a microstructure. WC-Co chosen in this experiment has a much larger Young's modulus and hardness than ordinary electroplated materials. The fabricated high-aspect-ratio WC-Co microstructures can have high resistance to buckling and wear when used as mechanical components or tools.

Received: 7 July 1999/Accepted: 25 November 1999

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A part of this work was performed under the management of the Micromachine Center under the Industrial Science and Technology Frontier Program, "Research and Development of Micromachine Technology", of MITI supported by the New Energy and Industrial Technology Development Organization. The authors gratefully acknowledge the assistance of students and researchers of WCAM in the University of Wisconsin at Madison.

This paper was presented at the Third International Workshop on High Aspect Ratio Microstructure Technology HARMST '99 in June 1999.

1 Introduction

High-aspect-ratio microfabrication technology covering a wide range of materials is desired for producing practical micro components. The LIGA process [Guckel et al. (1994)] has the capability of mass producing high-aspect-ratio microstructures with ultra fine patterns and extremely smooth sidewall surfaces. However, practical materials made by electroplating are limited to a few metals such as nickel, copper and their alloys. On the other hand, a micro-EDM [Masaki et al. (1990)] can produce three dimensional microstructures made from electric conductors. The fine surfaces of the structures are obtained by using a micro surface finishing method based on electrochemical etching [Takahata et al. (1997)]. However the conventional method using a single cylindrical tool electrode requires long machining times to produce patterned structures. The electrode is individually shaped by the wire electro-discharge grinding method (WEDG) [Masuzawa (1985)]. Replacement of the electrode is necessary due to its wear. It also takes a long time to shape and change the tool. This causes a decrease of EDMed shape accuracy due to the electrode positioning error or the variation of electrode dimensions. To solve these problems, a new fabrication process combining LIGA and the micro-EDM has been developed. This process enables one to obtain ultra fine patterned high-aspect-ratio microstructures made from various kinds of bulk materials, which cannot be produced by the conventional microfabrication methods. Such microstructures can be used not only as micro components for MEMS devices but also as tools for micro processing such as machining, measuring, manipulating, etc. WC-Co is one of the most useful materials for mechanical components and tools used in mechanical processes because of its excellent mechanical properties. With the developed process, high-aspect-ratio WC-Co microstructures have been produced with the idea of using such microstructures as practical tools for micro mechanical processing.

2 Fabrication process

Figure 1 illustrates the flow of the new fabrication process. The LIGA process (steps 1–5 in Fig. 1) developed by the University of Wisconsin at Madison [Guckel et al. (1990)] fabricates electroplated electrodes for the micro-EDM. The electrodes which are fabricated on a silicon substrate are

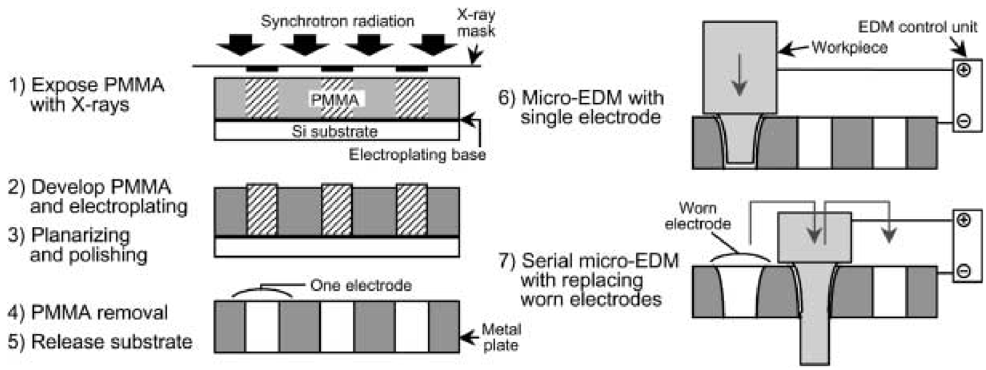

Fig. 1. Flow of new microfabrication process combining LIGA (step 1–5) and micro-EDM (step 6–7)

negative-type microstructures with ultra fine patterns. Several of the electrodes are easily formed in an electroplated metal plate. The metal plate which has the electrodes is released from the substrate as step 5 because the negative-type electrodes are self-supporting. The electrode location in the metal plate is extremely precise because photolithographic techniques are used for the electrode fabrication.

A positive-type patterned structure is produced by feeding the WC-Co workpiece into one of the electrodes with discharging as shown in the step 6. During this step the electrode shape is deformed due to its wear. To obtain a uniform cross-section along the workpiece's length, the electrode has to be replaced before its deformation occurs throughout its thickness. Such deformed electrode can be replaced with a new one by X–Y positioning between the workpiece and each of the electrodes. This can be done very accurately because of the precise location of the electrodes as shown in the step 7. A high-aspect-ratio patterned microstructure is obtained after repeating the machining and replacing processes.

3
Micro-EDM in the new process

Electrodes used in the conventional micro-EDM are required to have high wear resistance because replacing them during machining causes the problems described above. The electrode with a simple cylindrical shape has to be thin enough to machine a patterned high-aspect-ratio geometry by moving the tool along the pattern. As a result the electrode should be made from materials with high mechanical strength to obtain a straight shape. Tungsten meets these requirements and is usually used as the electrode material in the conventional method, however tungsten cannot be plated easily. In this new micro-EDM these problems are not so significant when compared with the conventional method because the replacement of arrayed electrodes can be executed quickly and accurately and the fully patterned electrodes which are supported by the metal plate are not required to have such high strength. This means that there is the possibility to choose other materials. Copper can be plated with adequate heights for the electrodes, but it is difficult to free the plated pieces from the same copper electroplating base on the silicon substrate. Nickel is therefore chosen as the electrode material in this experiment.

Figure 2 shows a schematic diagram of the setup for the micro-EDM. This is based on the Panasonic micro-EDM machine MG-ED72W. This setup has the Z stage for positioning the workpiece and the X–Y stage for positioning the metal plate with the electrode array to replace the worn electrodes. The positioning resolution is 0.1 μm. The metal plate is fixed on the holder which can be vibrated in the feeding direction of the workpiece. This vibration is necessary to avoid welding when a short circuit between the electrode and the workpiece occurs. This replaces electrode rotation of the cylindrical electrode in the conventional micro-EDM.

4
Experimental results

With the LIGA process an array of nickel electrodes with the negative-type gear pattern of 200 μm outside diameter was fabricated as shown in Fig. 3. The structural height is 300 μm. The initial shape of the electrode is shown on the left side of Fig. 4. It is deformed by wear as shown on the right side of Fig. 4 when the WC-Co workpiece with a diameter of 300 μm is fed into the electrode for about 400 μm with discharging. Although the length of the EDMed structure is limited to the feed depth in single machining, much taller heights can be obtained by repeating

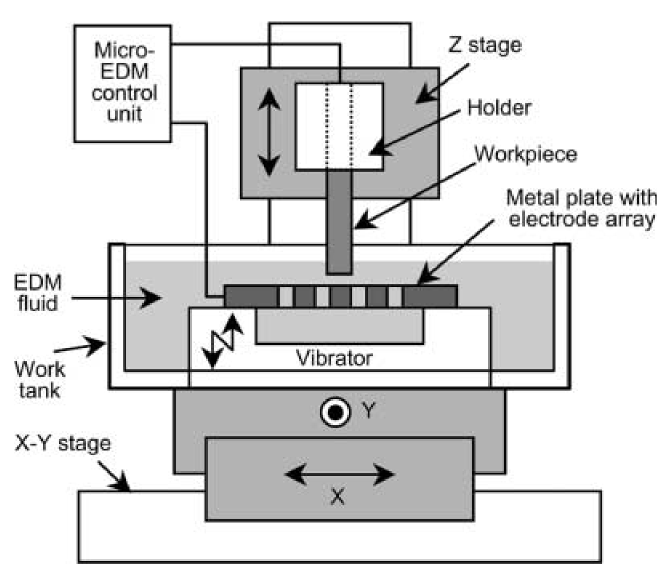

Fig. 2. Setup for micro-EDM in the new process

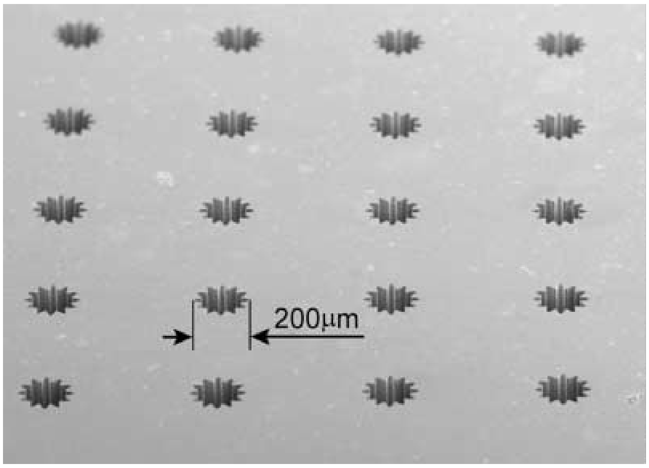

Fig. 3. Array of negative-type nickel electrodes fabricated by the LIGA process

the machining and replacing the worn electrode with a new one by X–Y positioning.

Figure 5 shows a positive-type WC-Co microstructure with a length of 1 mm produced by using three electrodes of the serial micro-EDM. Much higher aspect-ratio structures with length over 1 mm can be produced by increasing the replacement cycles. The variation of the outside diameter of the 1 mm long structure along its length has been measured and the result is shown in Fig. 6. This graph shows that this particular gear varies by about 4 µm in outside diameter along its length. The result shows that the new process enables the production of high-aspect-ratio microstructures from various bulk materials as well as WC-Co.

Figure 7 shows a gap between the initial shape of the electrode and the bottom of the EDMed gear. It is observed that there is a difference of 3 µm caused by the discharge gap. The gap is generally determined by the discharge energy and is stable under fixed discharge conditions. The dimension of the electrode patterns should be designed while keeping this gap in mind.

5
Properties of WC-Co structure

Figure 8 shows the distribution of the two mechanical properties of hardness and Young's modulus for WC-Co, typical electroplating materials and other substances. The chart shows that WC-Co has a much larger hardness than the electroplating materials. This means that WC-Co microstructures can achieve much higher resistance to mechanical wear caused by friction than the electroplated ones fabricated by the ordinary LIGA processes. WC-Co also has large Young's modulus when compared with electroplating materials and silicon. Silicon is a well-

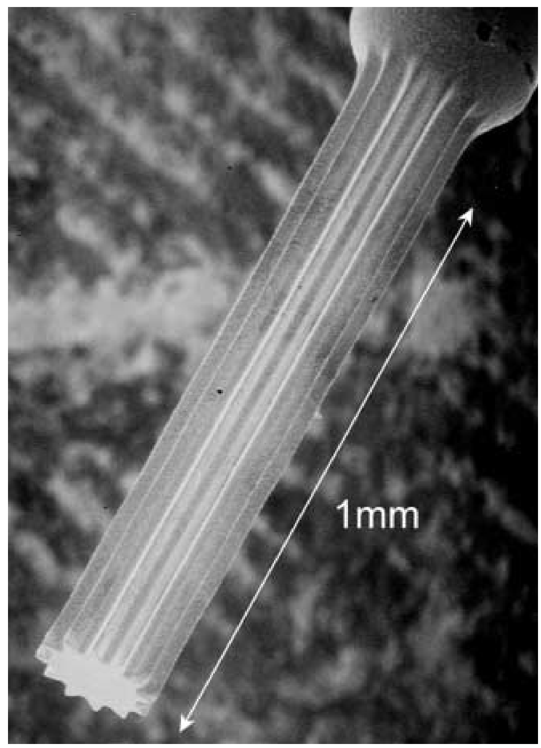

Fig. 5. 1 mm long WC-Co microstructure with gear pattern produced by the new process

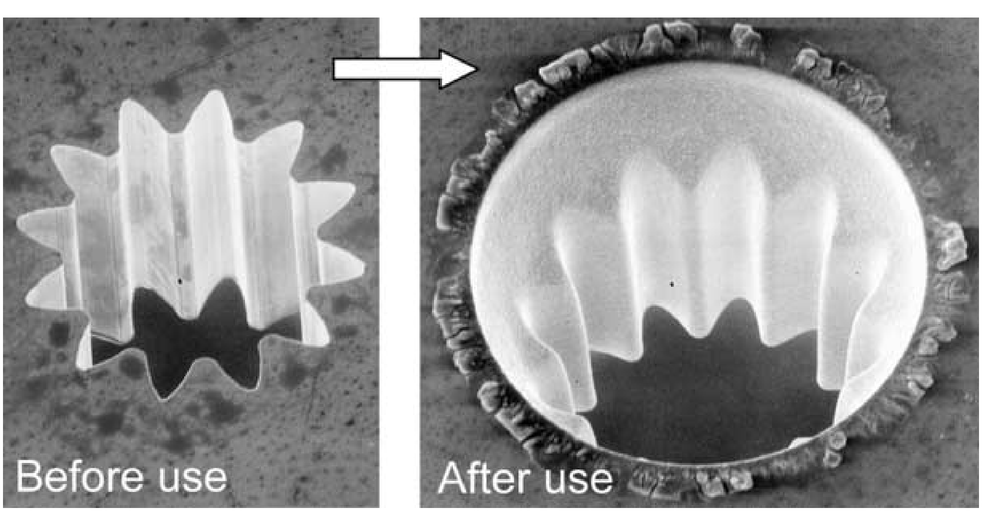

Fig. 4. Initial shape of patterned negative-type electrode and deformed one after use

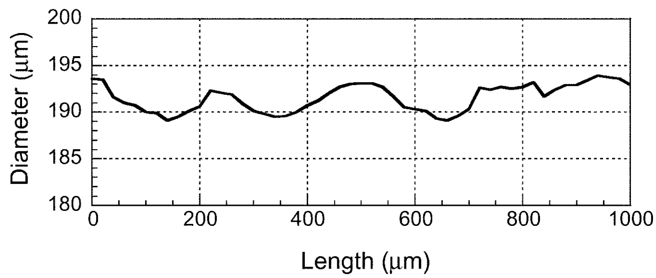

Fig. 6. Variation of outside diameter of 1 mm long gear in Fig. 5

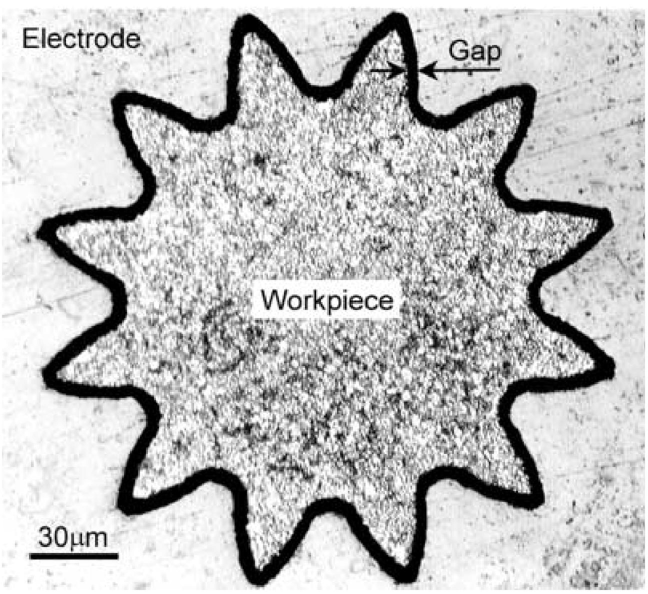

Fig. 7. Gap between electrode and EDMed workpiece (two superimposed photographs of electrode and workpiece with the same magnification)

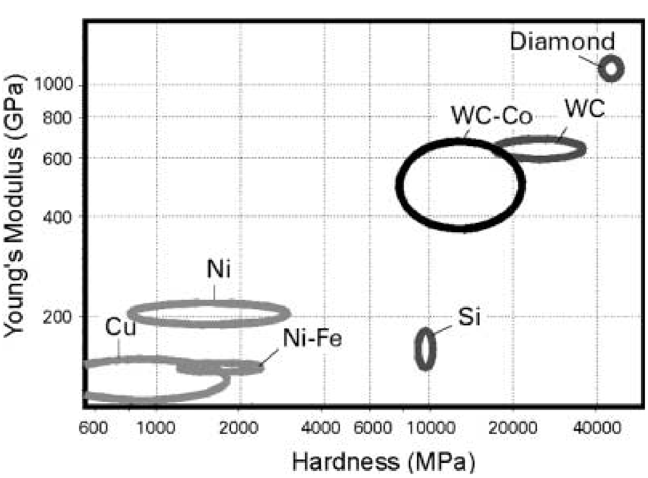

Fig. 8. Mechanical properties of WC-Co, electroplated materials and other substances

Table 1. Comparison of fracture toughness between WC-Co and other hard materials

	WC-Co	WC	Diamond	Si
Fracture toughness (MPa $m^{1/2}$)	9.6–22	2–3.8	3–3.7	0.7–0.9

known material which can be micromachined to high-aspect-ratio structures by etching technique such as deep RIE (reactive ion etching). A lot of applications for silicon microstructures have been realized in the MEMS field. However, WC-Co performs better than silicon when the microstructures have to have high stiffness such as high resistance to buckling. Figure 8 also shows that WC and diamond have larger hardness and Young's modulus than WC-Co, but those materials are brittle. Table 1 shows the comparison of fracture toughness between WC-Co and other hard bulk materials. This shows that WC-Co is about five times larger than WC in fracture toughness. This means that the produced microstructure shown in Fig. 5 may be adequate for use as a practical tool for mechanical processing such as cutting tools and dies if designed properly.

6 Conclusion

In conclusion, a new microfabrication process which combines with LIGA and micro-EDM has been developed. A high-aspect-ratio WC-Co microstructure with high precision was produced through the developed process. Since WC-Co has better mechanical properties than the other materials usually used in the MEMS field as far as resistance to buckling and wear are concerned, the produced WC-Co structure has the ability to be used as a mechanical processing tool. It is expected that the process will be used for producing practical micro mechanical components and micro processing tools by using suitable bulk materials for various purposes.

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