ULTRA PRECISION GRINDING IN THE FABRICATION OF HIGH FREQUENCY PIEZOCOMPOSITE ULTRASONIC TRANSDUCERS

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Abstract - High frequency ultrasonic transducers are needed for high spatial resolution measurements in applications such as medical diagnosis and non-destructive testing. However, cost-effective fabrication of high performance transducers with frequencies above 20 MHz is challenging because of the need for a thin layer of active material. Piezocomposites are the material of choice in such transducers at lower frequencies, but current fabrication methods cannot easily achieve sufficiently thin active layers. Commercially, piezocomposite is usually finished to thickness by grinding, providing surface finish acceptable for most applications. However, conventional grinding is insufficiently precise for high frequency operation and is subject to undesirable intra-process variation. The most widely used alternative is precision lapping and polishing, but this is slow and therefore expensive. In the work reported here, an alternative process of ultra precision grinding was studied, using the Loadpoint PicoAce machine operating in the ductile machining mode. To determine the capabilities of this machine for piezo-composite processing, 1-3 connectivity material was fabricated using both a standard commercial process and a novel approach based on viscous polymer processing. Unsupported layers of piezocomposite of thickness much less than 100 μm have been achieved with surface roughnesses of less than 1 μm and minimal discontinuity between the ceramic and polymer phases. These results suggest that ultra precision grinding may have a role to play in practical implementation of high frequency piezocomposites for ultrasonic transducers.

I. INTRODUCTION

High frequency ultrasonic transducers are used for medical imaging requiring high spatial resolution, with examples in dermatology [1] and studies on the vascular system [2] and mice [3], as well as elsewhere. However, cost-effective fabrication of high performance transducers operating at frequencies above about 20 MHz is challenging because of the need for a thin layer of piezoelectric material. Piezocomposites are the material of choice in such transducers at lower frequencies because of their well known advantages including high electromechanical coupling coefficients, relatively low acoustic impedance and low extraneous modes. However, thin material is required for high frequencies; for example, the thickness is in the range 35 – 45 μm for a frequency of 50 MHz.

Such thicknesses of piezocomposite material are challenging to produce because the piezoceramic phase exceeds the capabilities of thin film [4] deposition processes such as sputtering and even convenient thick film procedures [5] such as sol gel deposition. In addition, whilst thinned bulk piezoceramic is viewed as the gold standard in terms of material properties, the necessary thinning process is time consuming and expensive. Net shape processing [6] can achieve the necessary piezoceramic thicknesses directly, but piezocomposite still requires processing from greater than final thickness to remove the ceramic stock and excess polymer.

The conventional grinding procedures used for thinning and surface finishing in commercial piezocomposite fabrication produce surfaces of an acceptable quality for transducers for most applications, but they are insufficiently precise for high frequency operation and are subject to undesirable intra-process variation. In this paper, results are reported from an alternative process of ultra precision grinding of piezocomposite material, where the term “ultra precision grinding” is used as a generic term for techniques involving surface finishing of a very precisely sized workpiece. The present work was carried out on the novel Loadpoint PicoAce machine (Loadpoint, Swindon, UK).

The prominent issues affecting high frequency transducer manufacture are discussed in Section II and ultra precision grinding itself is discussed in more detail in Section III. Experimental results are presented in Section IV, including scanning electron microscopy and surface profiling. Section V concludes the paper and suggests areas for further work.

II. COMPOSITE MANUFACTURE

During the fabrication of 1-3 connectivity piezocomposites, conventional lapping and grinding processes often lead to height variations between the different phases of the composite because of differences in the mechanical properties of the two constituent materials. Typically, the pillars of the active ceramic or crystal material abrade faster than the polymer [7] as the polymer is more able to compress during the material removal process and subsequently to expand. This leads to height differences and physical discontinuities at the boundaries between the different phases and hence to an uneven surface, as shown schematically in Figure 1.

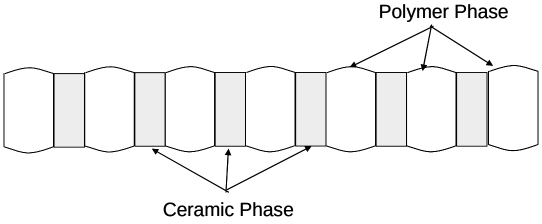

Fig. 1. Schematic diagram of piezocomposite material, indicating height difference between phases.

Figure 2 is an example of a surface profile from a conventional 1-3 connectivity composite after grinding to a thickness corresponding to operation at about 500 kHz. This shows more than ±15 μm variation, equivalent to about 80% of the active layer thickness of 35 – 45 μm required for a 50 MHz transducer made with piezocomposite. It is therefore clearly insufficiently precise for the thin layers required for high frequency operation.

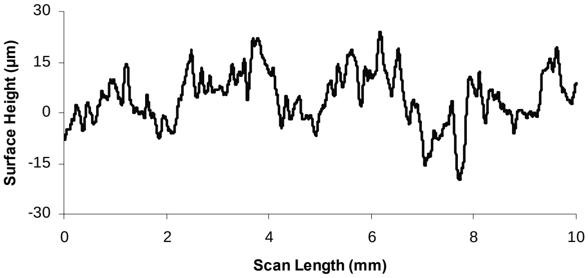

Fig 2. Surface profiles from piezocomposite showing roughness of more than ± 15 μm.

Precision lapping and polishing is a widely used substitute for fabrication in research and low volume manufacture. However, it is slow and therefore expensive, particularly when uniformity across two-phase materials such as piezocomposite is required. An alternative process is ultra precision grinding, using a machine such as the Loadpoint PicoAce.

III. ULTRA PRECISION GRINDING

The PicoAce is an ultra precision grinding machine capable of producing optical quality surface finishes and low levels of subsurface damage on a range of materials. It is suitable for traverse grinding of flat or convex surfaces up to 305 mm in diameter and plunge grinding up to a maximum diameter of 200 mm. Both material removal, typically in 10 μm steps, and surface finishing, typically to 1 μm roughness or less, are possible in a single automated process without requiring reconfiguration of the machining.

The general arrangement of the machine is shown in Figure 3, including the cup-wheel grinding spindle, the rotary work table and X- and Z-slideways mounted in a closed loop structure. The cup wheel spindle has a vertical axis and slides up and down in a cylindrical Z-slideway positioned centrally over the base, with the rotary table mounted on the X-slideway beneath. The PicoAce's main pyramidal space frame structure is extremely stiff [8] and all key elements are designed to maximise mechanical damping. The resonant frequency is very high, ultra high stiffness hydrostatic oil bearings are used on all slideways, and an air bearing is used for the grinding spindle.

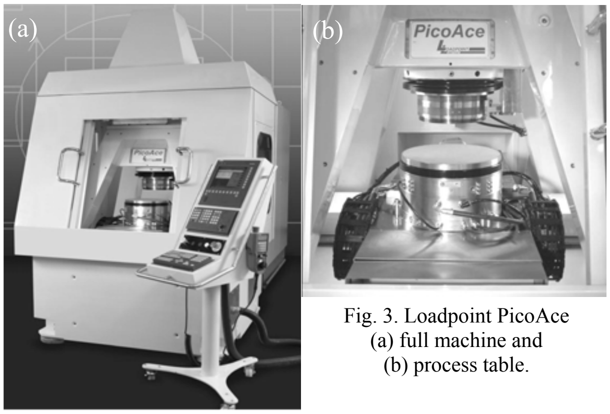

Fig. 3. Loadpoint PicoAce
(a) full machine and
(b) process table.

To avoid intra-process variation of the type sometimes found in conventional grinding, in-process grinding wheel conditioning is used, based on principles proved on a Tetraform C machine [8]. This machine has ground 6 Å Ra surfaces on quartz and 1.06 nm Ra surfaces on glass.

IV. Experimental Methods and Results

To test the capabilities of ultra precision grinding in the processing of piezocomposites, electromechanically hard and soft piezoceramics were investigated, bound in hard polymer matrices, typically RX771/HY1301 (Robnor Resins, Cambridge, UK). In the work reported here, three separate composite configurations were studied after being thinned to a thickness of approximately 50 µm. The first was a PZT 4D (Morgan Electroceramics, Ruabon, UK) piezocomposite made with standard dice and fill methods and processed by ultra precision grinding, denoted Sample A. Two composites designed specifically for high frequency operation were also investigated. These were made using a net shape process based on viscous polymer processing and mechanical pattern transfer [6]. The first sample was prepared by standard precision lapping, using a lapping/polishing machine (PM5, Logitech, Glasgow, UK), and is denoted Sample B(i), and the second sample was prepared with ultra precision grinding and is denoted Sample B(ii).

Figure 4 shows a detailed section of a scanning electron microscope (SEM) photomicrograph of Sample A after ultra precision grinding with the PicoAce. The surface of the ceramic is relatively rough at a microscopic scale while the surface of the polymer is smoother, indicating that grain pull-out may be occurring from the ceramic. However, there is little evidence of any physical discontinuity at the ceramic-polymer boundary.

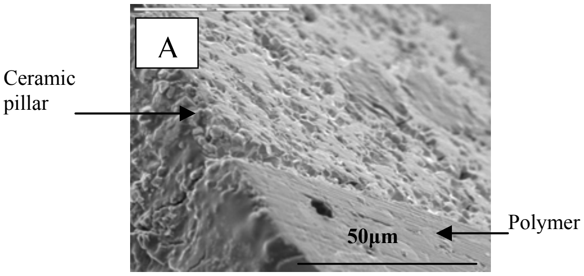

Fig. 4. SEM photomicrograph of boundary between ceramic pillar and polymer matrix in Sample A.

As further evidence of the surface quality, Figure 5 shows a surface profile of a pillar-polymer boundary in Sample A, measured with a DekTak 3ST surface profiler (Veeco, Cambridge, UK). It can be seen that the height difference between the pillar and polymer is limited to less than 1 µm and is therefore small enough to be suitable for high frequency devices. In addition, the overall surface roughness can be seen to be much better than that in Figure 2, produced with conventional grinding, with deviation not exceeding 3 µm.

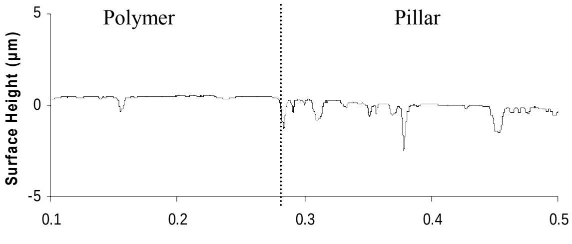

Fig 5: Surface profile from Sample A

Surface profiles from Sample B (i) after lapping and Sample B (ii) after ultra precision grinding are shown in Figure 6. Here, it can be seen that ultra precision grinding produces an improved surface finish when compared to lapping and less indication of discontinuity between ceramic pillars and binding polymer.

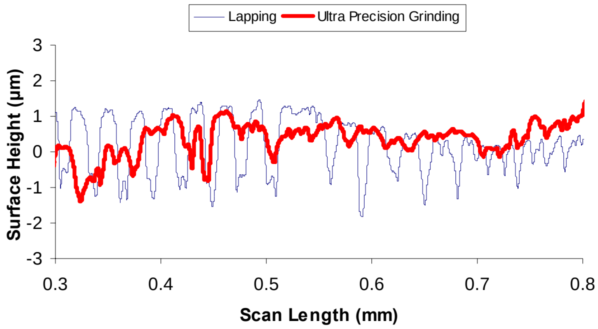

Fig. 6: Surface profiles from Sample B(i) (thin line) and Sample B(ii) (thick line).

V. CONCLUSIONS AND FURTHER WORK

The results reported here suggest that ultra precision grinding using a machine such as the Loadpoint PicoAce may have an important role to play in the practical implementation of high frequency piezocomposites for ultrasonic transducers. Unsupported layers of piezocomposite of thicknesses much less than 100 µm have been produced with surface roughnesses of approximately ±1 µm, commensurate with high frequency operation. Furthermore, there is reduced evidence of the physical discontinuities between the ceramic and polymer phases under SEM and surface profiling. The capability for combined removal of bulk material and surface finishing without manual intervention is particularly appropriate for volume production. However, there is some evidence of a better surface finish of polymer than ceramic. Therefore, further work will be carried out on process optimisation, both to improve the overall surface and to maximise the material removal rate.

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