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TITLE OF THE Ph.D. (Engg.) THESIS:

EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MACHINING PROCESS FOR MICROMACHINING APPLICATIONS

Abstract:

Innovations in the fields of biomedical devices, aerospace, automobiles, energy, optics, semiconductors, electronics and communications have led to miniaturization of the parts and devices. Small sized devices and their component parts are desirable to keep things compact and portable. Thus, material and energy required for manufacturing reduces drastically. As a result the cost of production and environmental pollution is reduced. Small parts have lower inertia because of which production process needs lesser time. Consequently, the productivity increases.

Micro machining is defined as the ability to produce micro features with the dimensions between 1 μm to 999 μm and the unit removal of the material is at the micron level. However, according to the Scientific Technical Committee of the Physical and Chemical Machining Processes of CIRP, acceptable dimension range for micro machining is 1 to 500 μm

Research on ultrasonic machining at the macro level has been already reported in various fields of industrial applications. However, downscaling of USM to micro level is essential to produce miniature features on parts of hard and brittle materials. Although some research work activities have already been carried out on ultrasonic micromachining process, in-depth studies and experimental investigation into ultrasonic micromachining of various engineering materials are very much demanded. Extensive research and technical improvement are needed to transform this USM technology into a capable and well-received technology for the successful adoptability of this process in fulfilling the needs of the modern micro-manufacturing industries. Keeping the above

considerations in view, the objectives of the present research work have been moduled as follows:-

(a) To study in depth ultrasonic micro machining setup for carrying out experimental investigation. To develop and modify micro tool holding and work holding unit of the existing USM setup which can be capable of performing investigation in the micro domain for micro machining of different ceramics.

(b) To develop cylindrical micro tools, multi tips micro tool and array of square micro tool for fabrication of micro holes, multiple micro channels and array of square micro holes by using USMM.

(c) To perform the experiments utilizing developed micro tools on micro-USM setup for generating micro holes on quartz. Experimental results will be further analyzed to study the influences of ultrasonic micromachining (USMM) process parameters on various responses.

(d) To develop empirical models for different responses, e.g. material removal rate (MRR), overcut and taper angle of micro holes on quartz during ultrasonic micromachining (USMM) based on Response Surface Methodology (RSM) utilizing experimental results and to analyse the influences of process parameters on the responses through response surface plots and contour plots based on developed empirical models.

(e) To perform single objective as well as multi objective optimization of response characteristics for determining optimal machining parametric combination in order to obtain the desired micromachining performance characteristics of ultrasonic micromachining (USMM) for generating micro holes.

(f) To perform the experiments utilizing developed multi tips micro tool on micro-USM to produce multiple micro channels on quartz as well as zirconia and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also to analyse various characteristics of machined surface through observation of micrographs.

(g) To perform experiments utilizing developed array of square micro tool on micro-USM to produce array of square micro holes on quartz and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also the characteristics of machined surface through observation of micrographs.

This research aims at a fundamental understanding of micro-USM process. It is expected that such an understanding will provide the necessary knowledge base for more reasonable process design and also determining optimally setting of ultrasonic micro machining conditions for micro machining applications. The use of developed micro tools and multi tips micro tools helps to carrying out experiments for generate micro hole, micro channels and array of micro holes to analyse the influence of process parameters on machining criteria. With the effective use of multi tip micro tools, machining time can be reduced and hence productivity increases for micro micromachining applications.

(i) Cylindrical micro tools, multiple tips micro tool and array of square micro tool have been successfully developed for in-depth experimental investigations into ultrasonic machining process and it is concluded that developed micro tools are capable to produce micro features on different hard and brittle materials such as quartz and zirconia.

(ii) Ultrasonic micromachining process has been successfully applied for generation of micro holes on quartz using the cylindrical shaped micro tool. From the experimental results, it can be summarized that performance of ultrasonic micro machining is very much influenced by abrasive slurry concentration compared to power rating and tool feed rate. For achieving higher MRR, higher power rating, higher abrasive slurry concentration and higher tool feed rate are preferred during USM for micro drilling on quartz. Higher MRR i.e. 0.376 mm^3/min is obtained at 400 W power rating. For achieving lower overcut and taper angle of micro hole, low value of abrasive slurry concentration, low value of power rating and low tool feed rate are to be selected during USM for micro drilling on quartz. Lesser overcut i.e. 55 µm and lesser taper angle i.e. 0.588^0 of micro hole is obtained at low value of abrasive slurry concentration during USM for micro drilling on quartz.

(iii) The developed mathematical models on MRR, overcut and taper angle are found as adequate to analyse the effects of process parameters on responses of micro hole on quartz by ultrasonic micromachining process. Form the response graphs based on RSM models; it is observed that MRR increases with increases in abrasive slurry concentration with little variation on values

of power rating. Lower overcut has been achieved with a combination of medium power rating and higher value of slurry concentration. Lower value of taper angle has been observed at the medium value of tool feed rate and medium value of abrasive slurry concentration.

(iv) Based on single objective optimization, for achieving maximum MRR, the optimal combination of process parameters obtained as abrasive slurry concentrations of 31.71 %, power rating of 400 W and tool feed rate of 1.03 mm/min. The maximum MRR is obtained as 0.4631 mm^3/min. For achieving minimum overcut the optimal combination of process parameters obtained as abrasive slurry concentrations of 20 %, power rating of 200 W and tool feed rate of 0.8 mm/min. The minimum overcut is obtained as 30.16 µm. For achieving minimum taper angle the optimal combination of process parameters obtained as abrasive slurry concentrations of 30 %, power rating of 220.20 W and tool feed rate of 0.90 mm/min. The minimum half taper angle is obtained as $0.3371^{0.}$

(v) The multi objective optimization has also been performed based on developed mathematical models to obtain the optimal setting of process parameters for maximum material removal rate, minimum overcut and minimum taper angle. The optimal combination is obtained as: abrasive slurry concentration of 23.43 %, power rating of 290 W and tool feed rate of 0.80 mm/min. The maximum value of MRR is obtained as 0.2008 mm^3/min. The minimum value of overcut is achieved as 50.29 µm and the minimum value of taper angle is achieved as 0.7880^0.

(vi) The experiments are conducted at optimal process parametric settings and the percentage of errors based on the results of actual and predicted values of responses for single objective as well as multi objective optimization lie within 5%. Therefore, the results are quite adequate and acceptable.

(vii) One of the significant contributions of the present research is generation of multiple micro channels on quartz. Multiple micro channels on quartz has been successfully produced by ultrasonic micromachining process utilizing developed multi tips micro tool. Micro USM process parameters have a significant effect on MRR, width overcut, taper angle and surface roughness. The aspect ratio of micro channel has been obtained as 3. The lesser width

overcut of micro channel is obtained as 16 μm at slurry flow rate of 60 ml/sec. The lesser value of taper angle obtained is obtained as 1.31^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.657 μm at lower abrasive slurry concentration. Based on SEM micrographs, some phenomena such as micro chipping and edge chipping is also observed at bottom surface and both sides of entrance surface of the machined micro channels.

(viii) Multiple micro-channels are also successfully fabricated on zirconia by micro ultrasonic machining process utilizing developed multi tips micro tool and can be considered as a major contribution of the present research. The aspect ratio of micro channel has been obtained as 3. From the experimental result it can be observed that best width overcut of micro channel is obtained as 26 μm at tool feed rate of 0.8 mm/min. The lesser value of taper angle obtained is obtained as 0.931^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.117 μm at lower slurry flow rate. The machined surface topography consists of the alteration such as edge chipping, micro-cavities, micro-crack on the surface at high power rating as observed through SEM micrographs.

(ix) Array of square micro holes are successfully fabricated on quartz by ultrasonic micromachining process utilizing developed multi tips square micro tool and can also be considered one of the significant contributions of this investigation. From the experimental result, it has been observed that lower width deviation of micro holes is obtained as 37 μm and lower taper angle is 1.109^o at 5 % abrasive slurry concentration. The lower value of angular deviation is obtained as 0.836^o at lower power rating. The higher MRR is obtained as 1.427 mm^3/min at 25% abrasive slurry concentration. Based on SEM micrographs, it can be observed that the machined surface topography consists of the alteration such as edge chipping, shallow micro dent at bottom surface, at high power rating.

The author has made sincere efforts to present the research work by exploring the machining of quartz and zirconia for generation of micro holes, micro channels, and array of square micro holes on quartz as well as zirconia utilizing cylindrical shaped and multiple tips micro tools. This experimental investigation and discussion will be useful to

researchers, scientists as well as engineers who are working on ultrasonic machining in micro domain with different hard and brittle materials. It can also provide direction for development of micro tools for ultrasonic machining for industrial applications in micro domain and also for fabrication of different complex micro features on various hard and brittle materials, which have prospective applications in biomedical science, micro fuel cell and cooling components of micro electronics, micro-electro-mechanical system (MEMS), optical interconnection, inkjet printer, aerostatic air bearing system etc.