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Experimental Investigation on Over-Cut in Ultrasonic Machining of WC-Co Composite

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Abstract**—**Ultrasonic machining is one of the most widely used non-traditional machining processes for machining of materials that are relatively brittle, hard, and fragile such as advanced ceramics, refractories, crystals, quartz etc. Present article has been targeted at investigating the impact of different experimental conditions (power rating, cobalt content, tool material, thickness of work piece, tool geometry, and abrasive grit size) on over cut in ultrasonic drilling of WC-Co composite material. Taguchi's L-36 orthogonal array has been employed for conducting the experiments. Significant factors have been identified using analysis of variance (ANOVA) test. The experimental results revealed that abrasive grit size and tool material are most significant factors for over cut.

Keywords**—**ANOVA, Abrasive grit size, Taguchi, WC-Co, ultrasonic machining**.**

I. INTRODUCTION

ULTRASONIC Machining is mechanical type non-traditional machining process used for machining hard and brittle materials (glass, ceramics, silicon, semiconductors, ferrites etc.) [1]. Abrasive grit size and power rating are the main significant factors which affect the material removal rate and tool wear rate [1]. Lalchhuanvela et al. [2] investigated the effect of different process parameters on the material removal rate and surface roughness in machining of alumina based ceramics. It was reported that the higher level of every input parameter gives higher MRR. Surface roughness was reported to be decreased with the reduction in grit size and power rating. Slurry concentration, tool feed rate, and slurry flow rate have less effects on surface roughness. Kumar et al. [3] reported that the tool material and power rating affect the wear of the tool to a significant extent, while slurry concentration has no appreciable effect on tool wear rate.

Singh et al. [4] investigated the machinability of commercially pure titanium in ultrasonic machining using graph theory and matrix method. Komaraiah and Reddy [5], Kumar and Khamba [6] and Dam et al. [7] assessed the impact of work material properties on machining characteristics in ultrasonic machining. Results reported that work materials with higher hardness and fracture toughness tend to be machined at higher removal rates.

Tungsten carbide has been well known for its exceptional hardness and wear/abrasion resistance; however, it also possesses poor toughness. Matrices of ductile metals, such as cobalt, nickel greatly improve its toughness. Tungsten carbide-cobalt composite (usually WC–Co), which consists of tungsten carbide grains embedded in a metal binder phase, exhibits high hardness to combat wear and sufficient toughness to withstand interrupted cuts or vibration occurring during the machining process. WC-Co composite material is also termed as Cemented carbide, hard metal and in some cases, cermets [8]. Cemented tungsten carbide (WC-Co) is a hard material with its excellent hardness, wear resistance, good dimensional stability and high mechanical strength.

As per the current trends in manufacturing, WC and its composite (WC–Co) are of great importance in the production of cutting tools, dies and other special tools because of their superior characteristics maintained over a wide range of temperature. However, due to these distinguished properties, complex shapes and precise dimensions by the conventional machining methods cannot be accomplished [8], [9]. WC-Co composite when machined by conventional machining process (CNC turning using CBN tools), results in higher cutting force, poor surface finishing and low material removal rate [8]-[12]. A number of studies have also reported the application of non-traditional machining methods such as electro-discharge machining (EDM), wire EDM, laser beam machining etc. [8]-[12]. The following problems have been encountered in these studies.

- The problem in electrical discharge machining is related to the differences in the physical properties of WC and Co such as melting and evaporation temperatures, thermal expansion and contraction coefficient and electrical conductivity. The lower melting point of the binder phase (Co) causes melting of this material before tungsten carbide (WC) and causes the WC grains to dislodge during the process. The carbon content of WC is high (6.13% by weight) and WC can be dissociated into W2C and graphite if the process energy is high enough. The graphite and the released WC grains can agglomerate, making the discharge condition unstable and prone to arcing. This affects the machined surface topography and surface integrity.
- Machining of WC-Co composite with EDM also causes a significant amount of cracks and spalling on the machined surface which results in decreased hardness, wear resistance and corrosion resistance of machined surface. These defects affect the product quality and service life of the machined component.

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- Electrical discharge-drilling of WC-Co suffers from severe electrolytic corrosion around the machined holes because cobalt is easily dissolved in water.

Ultrasonic machining could be a viable alternative for machining of WC-Co composites, as the process is free from many of problems associated with thermal-based machining. The present investigation focuses on the accuracy of the drilled hole through the study of the effects of process parameters on over cut in ultrasonic drilling operation.

II. EXPERIMENTATION

In this article, work materials with the cobalt content of 6% and 24%, with 3 mm and 5mm thickness were selected. Tools were made of three different materials; stainless steel, silver steel and nimonic-80A. The designing of tools was performed by giving adequate consideration to the tool weight (9 g). Tools were fabricated in two profiles-solid and hollow. Boron carbide was used as abrasive with three different grit sizes (200, 320 and 500). The abrasive slurry was prepared with a concentration of 25% (by weight). Power rating was selected at three discrete levels as 40%, 60%, and 80%.

The experiments were performed on an ‘AP-450 model Sonic-Mill’ ultrasonic machine (Sonic-Mill, Albuquerque, USA). The different sub systems of USM setup consist of power supply system, mill-module unit, abrasive slurry supply system, and work piece holder. Fig. 1 shows the tool, horn, workpiece and fixture used in the ultrasonic drilling.

In this study, Taguchi’s L-36 orthogonal array has been used for planning and designing of the experiments. The experimental plan is exhibited in Table I. There are three factors with two levels and remaining factors have three levels. In addition, three interactions (A×D, B×D, C×D) are also required to be evaluated. Therefore, the degrees of freedom of L-36 array (35 DOF) are adequately enough for the problem under consideration (with required DOF being 15). The different process variables and the selected interactions are allocated to the specified columns of the orthogonal array (OA) using triangular and line graph specified for L-36 OA. According to the design matrix, holes were drilled in work samples for different experimental conditions. Two replications of entire experiment, which consist of 72 experimental trials in total, were conducted. The experiments were conducted in purely random order so as to tackle the variation caused by noise factors. For estimation of S/N ratio, following relations have been used [13].

Smaller the best:

$$\left(S/N\right)_{SB} = -10\log\left(\frac{1}{R}\sum_{j=1}^{R} y_j^2\right) \qquad (1)$$

where y_j is the response value recorded in j^{th} observation. Here, for over cut, “smaller the best” type S/N ratio were computed.

To compute the over-cut, the hole oversize was determined first by measuring the difference between the tool diameter (before machining) and hole diameter at the entry side of the hole. The measurements were carried out by using digital vernier caliper (Mitutoyo make, least count-1 µm). Thereafter, the over-cut was computed as half of the hole oversize, for taking the deviation in one direction only.

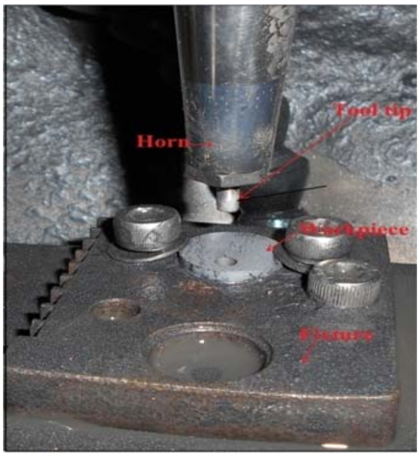

Fig. 1 Machining zone

III. RESULTS AND DISCUSSION

Fig. 2 shows the mean effect plots raw data for over cut. Work material properties have significant effect on the over cut. Over cut decreased with increased in cobalt content in work material. Thickness of work material has no appreciable effect on over cut.

Tools with solid profile have produced more over cut as compared to hollow tools. Using hollow tool, cutting time is reduced due to efficient flow of abrasive particles. Due to this fact, the hole over cut is reduced, as the machining in the lateral direction is sustained for less duration. The tools material can be ranked in order of decreasing over cut as; nimonic-80A > stainless steel > silver steel. Over cut is increased with increasing grit size.

The average over cut is least for fine sized grit (mesh 500). Larger particles erode bigger chunks of material from the lateral surface, resulting in higher oversize. Power rating has less effect as compared to grit size. The over size is minimum at the mid-level of power rating and becomes higher at both extremes (40%, 80%). At highest level of power rating, the lateral vibrations of tool get increased. At the lower level (40%), the machining is sustained for longer time, which generates higher over cut. Fig. 3 shows the mean effect plot for S/N ratio.

The interaction effects for raw data have been shown in Fig. 4. There are significant interactions between profile of tool and tool material, thickness of work material and tool material, and cobalt content and tool material with regard to the raw data.

The optimal parametric setting for over cut (for mean value as response) is; work material with 24% cobalt content, thickness of work - 3 mm, profile of tool -hollow, tool material -sliver steel, grit size - 500 mesh and power rating - 60%.

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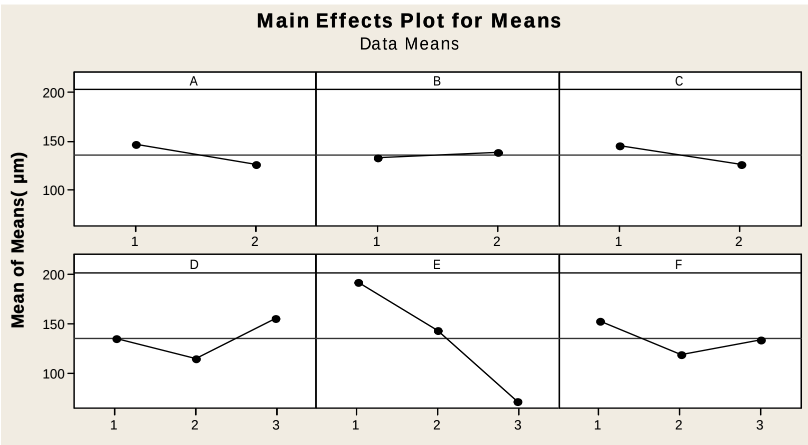
TABLE I
DESIGN MATRIX FOR L_{36} ORTHOGONAL ARRAY

Exp. No	Cobalt (%) content	Thickness of work	Profile of tool	Tool material	Grit size (mesh)	Power rating (% of max. rating)
1	6 %	3 mm	Solid	Stainless steel (T1)	200	40
2	6 %	3 mm	Solid	Stainless steel (T1)	320	60
3	6 %	3 mm	Solid	Stainless steel (T1)	500	80
4	6 %	5 mm	Hollow	Stainless steel (T1)	200	40
5	6 %	5 mm	Hollow	Stainless steel (T1)	320	60
6	6 %	5 mm	Hollow	Stainless steel (T1)	500	80
7	24 %	3 mm	Hollow	Stainless steel (T1)	200	40
8	24 %	3 mm	Hollow	Stainless steel (T1)	320	60
9	24 %	3 mm	Hollow	Stainless steel (T1)	500	80
10	24 %	5 mm	Solid	Stainless steel (T1)	200	40
11	24 %	5 mm	Solid	Stainless steel (T1)	320	60
12	24 %	5 mm	Solid	Stainless steel (T1)	500	80
13	6 %	3 mm	Solid	Silver steel (T2)	200	60
14	6 %	3 mm	Solid	Silver steel (T2)	320	80
15	6 %	3 mm	Solid	Silver steel (T2)	500	40
16	6 %	5 mm	Hollow	Silver steel (T2)	200	60
17	6 %	5 mm	Hollow	Silver steel (T2)	320	80
18	6 %	5 mm	Hollow	Silver steel (T2)	500	40
19	24 %	3 mm	Hollow	Silver steel (T2)	200	60
20	24 %	3 mm	Hollow	Silver steel (T2)	320	80
21	24 %	3 mm	Hollow	Silver steel (T2)	500	40
22	24 %	5 mm	Solid	Silver steel (T2)	200	60
23	24 %	5 mm	Solid	Silver steel (T2)	320	80
24	24 %	5 mm	Solid	Silver steel (T2)	500	40
25	6 %	3 mm	Solid	Nimonic-80A (T3)	200	80
26	6 %	3 mm	Solid	Nimonic-80A (T3)	320	40
27	6 %	3 mm	Solid	Nimonic-80A (T3)	500	60
28	6 %	5 mm	Hollow	Nimonic-80A (T3)	200	80
29	6 %	5 mm	Hollow	Nimonic-80A (T3)	320	40
30	6 %	5 mm	Hollow	Nimonic-80A (T3)	500	60
31	24 %	3 mm	Hollow	Nimonic-80A (T3)	200	80
32	24 %	3 mm	Hollow	Nimonic-80A (T3)	320	40
33	24 %	3 mm	Hollow	Nimonic-80A (T3)	500	60
34	24 %	5 mm	Solid	Nimonic-80A (T3)	200	80
35	24 %	5 mm	Solid	Nimonic-80A (T3)	320	40
36	24 %	5 mm	Solid	Nimonic-80A (T3)	500	60



A-Cobalt content, B-Work thickness, C-Tool profile, D-Tool material, E-Grit size, F-Power rating

Fig. 2 Mean effect plot for over cut (raw data)

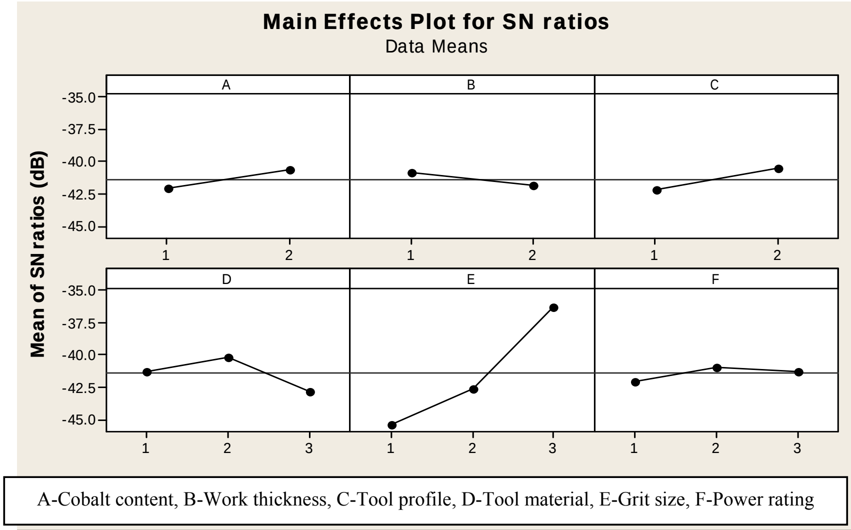


Fig. 3 Mean effect plot for over cut (S/N data)

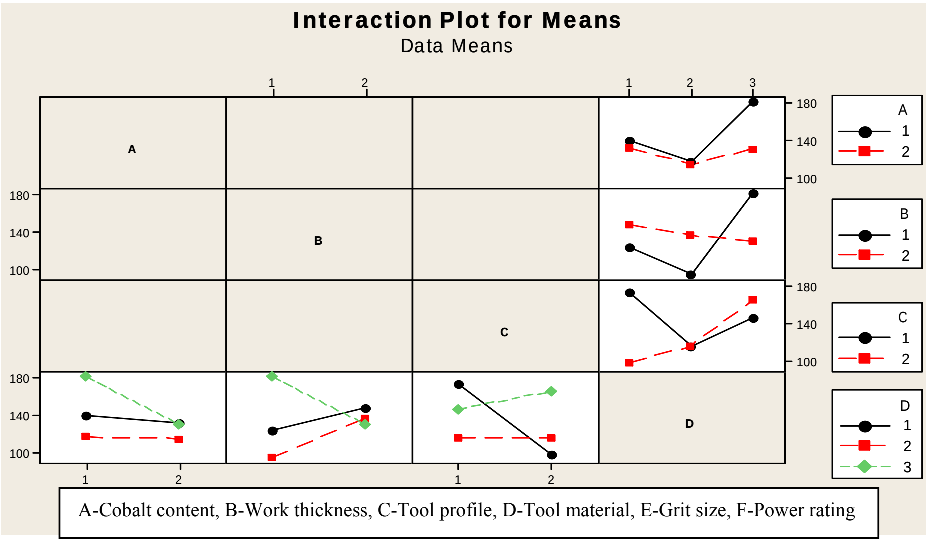


Fig. 4 Interaction plot for over cut (raw data)

TABLE II
ANOVA RESULTS FOR OVER CUT

	Over cut (raw data)			Over cut (S/N ratio)		
Source	***DOF***	***F***	***P***	***DOF***	***F***	***P***
A	1	8.73	0.005*	1	2.81	0.110
B	1	0.50	0.481	1	1.18	0.290
C	1	7.56	0.008*	1	4.11	0.056
D	2	11.73	0.000*	2	3.22	0.061
E	2	106.32	0.000*	2	40.07	0.000*
F	2	8.00	0.001*	2	0.53	0.599
A×D	2	4.95	0.011*	2	0.32	0.730
B×D	2	16.98	0.000*	2	4.37	0.027*
C×D	2	18.14	0.000*	2	7.58	0.004*
Error	56			20		
Total	71			35		

A-cobalt content, B-thickness of work piece, C-tool geometry, D-tool material, E-grit size, F-power rating, *F*- Fisher's ratio, *P*- Probability value, *Significant at 95% confidence level.

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ANOVA test has been performed to identify the significant parameters. Table II shows the ANOVA results for over cut (raw data and S/N data). The significant parameters are; cobalt content, tool profile, tool material, grit size and power rating. In addition, interaction between cobalt content and tool material, work piece thickness and tool material and, tool profile and tool material are significant. Grit size is the most significant parameter which affects the over cut. The predicted optimal value of overcut is computed as 24 µm, which is validated by confirmation experiments (26 µm).

IV. Conclusions

The aim of this investigation is to study the effects of several important parameters on over cut in the ultrasonic machining of WC-Co composite. On the basis of above following conclusions can be drawn;

- The optimal parametric setting for over cut; work material with 24% cobalt content, thickness of work is 5mm, profile of tool is hollow, tool material is silver steel, grit size is 200 mesh, and power rating is 40%.
- Grit size is the main significant factor which affect the over cut.
- ANOVA results show that the cobalt content, tool profile, tool material, grit size and power rating are the significant, and interaction between cobalt content and tool material, work piece thickness and tool material and, tool profile and tool material are also significant.
- The optimized value of over-cut (24 µm) has been validated through confirmation experiments, which indicated a good agreement between the two values.

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