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An experimental study on ultrasonic assisted drilling of stainless steel AISI SUS 304

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ABSTRACT: Stainless steel is considered as a difficult-to-cut material, especially for deep drilling. The deep drilling, where the aspect ratio of the hole depth and diameter is larger than 5, usually required special tools and techniques, such as peck drilling or high pressure cooling to be completed. This paper presents experimental study on a new technique of applying ultrasonic assisted drilling (UAD) in deep-hole drilling with aspect ratio of 8 for stainless steel using typical twist drill bits. Under low cutting speed in the range from 300 to 550 rpm and a low feed rate of 0.05 mm/rec, both CD and UAD were able to continuously complete the deep holes. The effects major parameters, including cutting speed, feed rate and drilling methods are evaluated using Taguchi design of experiment and ANOVA analysis. The results revealed that, the spindle speed is the most factors has significant effect on thrust force, drilling torque and work done. Under the same cutting parameters of cutting speed and feed rate, ultrasonic assisted drilling process constitutes considerable smaller thrust force, drilling torque and work done compared to those of conventional drilling.

KEYWORDS: Conventional drilling, Ultrasonic assisted drilling, deep holes, thrust force, drilling torque, work done.

I. INTRODUCTION

Until now, drilling difficult-to-cut materials, such as SUS 304, duplex stainless steel, Ti-6Al-4V… is still a challenge due to the ductility or the high strength and low thermal conductivity of them. Compared to turning and milling, drills are subjected to severe machining conditions such as higher thrust force, poor chip evacuation and chip jamming, as a result of the depth of the cutting zone within the workpiece [1], and thus considered the most complex and challenging metal cutting operations [2],[3],[4],[5]. The cutting process becomes more difficult and complex in deep hole drilling, where the hole depth, L is of above five times the drill bit diameter, D [1]. However, drilling is still the most commonly used method. It represents 40% to 60% of the total material removed in the aircraft frame industry [2]. According to [6], almost 99% of the energy fed to the machine tool is converted into heat. The application of cooling is needed to reduce the generated cutting temperature at the machining area. However, in drilling, the coolant maybe does not sufficiently reach to the drill tip at the cutting zone because of the counter flow of the chips limits further penetration, especially in deep-hole drilling. To overcome such problems during direct drilling, different drilling techniques were used, such as peck drilling [2],[7],[8], ultrasonic assisted directly drilling [9],[10],[11]…

This paper presents an experimental study on ultrasonic assisted drilling (UAD) and conventional drilling AISI 304 stainless steel in terms of thrust force, drilling torque and work done. Design of experiments was prepared using Taguchi orthogonal array of L8 and experiments were performed with two levels of the cutting parameters.

II. EXPERIMENTAL DETAILS

The workpieces used for these experiments are made from AISI 304 stainless steel bars. The composition of AISI 304 stainless steel is shown in Table 1. The dimensions of the workpieces were 10 mm in diameter and 40 mm in length. The drill bits used in this work were HSS-Co, which was 5 mm in diameter, 55 mm in flute length, 105 mm in overall length, right hand helix, and a point angle of 135°. Drilling processes were performed using the conventional turning machine, model Takisawa TSL-550. Experiments were conducted using flood cooling. The solution including of 5% emulsion and 95% normal water was used as cutting fluid. A series of pilot test found that all the deep drilling processes can be done at a low feed rate of 0.05 mm/rev.

In order to investigate the effect of UAD process on the thrust force, drilling torque and work done, two different drilling processes were carried out in this work, namely, ultrasonic assisted drilling (AUD) and conventional drilling (CD). For each drilling process, the holes were directly drilled in

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each of the two workpieces using a new drill bit. The feed rate, f_r = 0.05 mm/rev, was kept constant. An ultrasonic generator (model MPI WG-3000 WG, MP Interconsulting Company, Switzerland) was used to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency, f range of the generator is from 20 kHz to 40 kHz and the frequency step is 1 Hz. A Herrmann KHS20-IP50-L transducer, working at 20 kHz frequency, was used to convert the ultrasonic power to mechanical vibration of the drilling bit. The amplitude of ultrasonic vibration is equal to 10 μm. The parameter chosen studying on drilling process was spindle speed, n with two levels and such process with two levels, i.e UAD or CD (Table 2).

Figure 1 shows the typical plots of thrust force cutting and drilling torque. As can be seen Figure 1, the drilling process was divided into three stages. The stage (I) corresponds to the engaging of the drill cutting edges into the material to-be-cut. In this stage, the cutting torque gradually increased.

Table 1. Chemical composition of AISI 304

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Fe
%	0.07	0.75	2.0	0.045	0.030	19.5	10.5	1.24	Balance

Table 2. Drilling factors and their levels

Factors	**Unit**	**Level 1**	**Level 2**
Spindle speed, n	rpm	300	550
Processes, V (frequency f; amplitude A)	-	CD (f = 0, A = 0)	UAD (f = 20 kHz; A = 10 μm)

In the stage (II), the drilling torque and thrust force becomes stable. Due to drilling is the complex process, the chip evacuation and chip jamming maybe occurred in this stage. So, thrust force varies continuously and irregularly (noted by "fluctuation" on the Figure 1), while drilling torque usually increases with drill depth. Maximum values, mean values of the torque and thrust force in this stage were selected for analysis. The stage (III) corresponds to the unstable process corresponds to the end of process, after the whole hole is drilled. In this stage, both thrust force and drilling torque fast decrease.

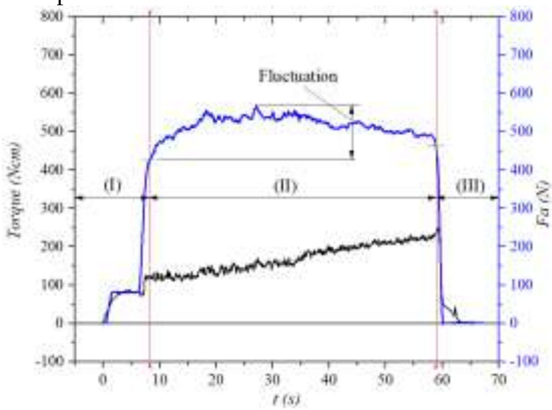

Figure 1. Plots of thrust force cutting F_a (blue line) and torque drilling (dark line) during drill process

In many previous studies, drilling torque and thrust force are the two major factors used to examine drilling operation. However, it can be not easy to directly compare the processes because those factors varied. Especially, the fluctuation and increasing of the drilling torque and thrust force are observed typical phenomena in deep-holes drilling (see Figure 1). Several attempts have been implemented, such as using maximum or average forces to evaluate the processes. Consequently, beside the drilling torque and thrust force, total energy consumed for each process should be an important factor to be considered. It is noted that, a process having small thrust force but take for long time would consume more energy than the one with higher thrust force acting in shorter time. The total work done for each drilled hole can be calculated as following:

$$W = W_T + W_{Fa} \quad (1)$$

where W_T is the work done by the drilling torque, and W_{Fa} is the work done by thrust force. These work done components can be carried out from the area under the corresponding plots,

$$W_T = \int_0^{t_{dr}} \frac{T.\omega}{100} dt = \frac{\pi.n}{30.100} \int_0^{t_{dr}} T dt = \frac{A_T.\pi.n}{3000} \ (J) \quad (2)$$

and

$$W_{Fa} = \int_0^{t_{dr}} \frac{F_a.f.n}{60.1000} dt = \frac{A_{F_a}.f.n}{60000} \ (J) \quad (3)$$

Because the drilling torque T and thrust force F_a are changed during the machining process, each of such components can be calculated as below.

where t_{dr} is the time required to complete the hole (in sec), T is the drilling torque (in N.cm), F_a is the thrust force (in N), f is the feed rate (in mm/rev), and n is the spindle speed (in rpm), A_T is the area under the drilling torque T plot, and A_{Fa} is the area under the thrust force F_a plot.

According to the Taguchi L8 in design of experiments, 8 combinations of drilling parameters were designed and experiments performed. Table 3 shows the S/N ratios calculated with Taguchi method for maximum drilling torque (T_max), maximum thrust force (F_a_max) and drilling work done, using smaller the better characteristic and S/N ratios.

Table 3. DOF and experimental results of maximum drilling torque (T_max), of maximum thrust force (F_a_max) and of work done.

Spindle speed, n (rpm)	Processes, V	T_max (N.cm)	F_a_max (N)	Work done (J)	S/N T_max	S/N Fa_max	S/N Work done
300	CD	226.997	571.115	8093.76			
300	CD	250.341	600.000	8440.22	-47.12	-55.13	-78.16
300	UAD	290.330	480.270	7530.68	-47.97	-55.56	-78.53
300	UAD	313.403	561.627	7668.50	-49.26	-53.63	-77.54
550	CD	217.459	475.660	5511.62	-49.92	-54.99	-77.69
550	CD	257.990	550.980	5950.11	-46.75	-53.55	-74.83
550	UAD	169.550	455.310	4999.26	-48.23	-54.82	-75.49
550	UAD	184.049	497.300	5243.38	-44.59	-53.17	-73.98

III. ANALYSIS OF THRUST FORCE

S/N ratios were calculated with Taguchi method for maximum thrust force (F_a_max) using smaller the better characteristic and S/N ratios are shown on the Table 4. In the ANOVA, at a confidence level of 95.1%, the experimental results and the Taguchi S/N ratios were evaluated as shown in Table 4. ANOVA also determined the contribution of individual parameters on the maximum thrust force. According to the ANOVA for S/N ratio of thrust force, the spindle speed is showing more contribution of 56.4%. Herein, the error was found as 1.64%.

Figure 2 shows mean of F_a_max (left figure) and mean of S/N ratios to the levels of drilling parameters (right figure). As can be seen, the suitable levels of drilling parameters are 550 rpm spindle speed and UAD process for minimum value of maximum thrust force. It can be said that, UAD process is better than CD and the high speed of spindle is better than low speed in term of thrust force.

IV. ANALYSIS OF DRILLING TORQUE

For maximum drilling torque (T_max), S/N ratios were calculated with Taguchi method using smaller the better characteristic and S/N ratios are shown on the Table 5. In the ANOVA, at a confidence level of 53.6%, the experimental results and the Taguchi S/N ratios were evaluated as shown in Table 5. ANOVA also determined the contribution of individual parameters on the maximum drilling torque. According to the ANOVA for S/N ratio of thrust force, the spindle speed is showing more contribution of 50.0%. Here, the error was found as 49.3%.

Figure 3 shows mean of T_max (left figure) and mean of S/N ratios (right figure) to the levels of drilling parameters. As can be seen, the more suitable levels of drilling parameters are spindle speed of 550 rpm and UAD process for minimum value of maximum drilling torque. The same as thrust force, it can be assumed that, UAD is better than CD and the high spindle speed is better than low speed in term of T_max.

Table 4. Analysis of Variance for Signal to Noise Ratios (for F_a_max)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
n	1	0.92075	0.92075	0.92075	34.49	0.107	56.4
V	1	0.68615	0.68615	0.68615	25.70	0.124	42.0
Error	1	0.02670	0.02670	0.02670			1.6
Total	3	1.63360					100.0

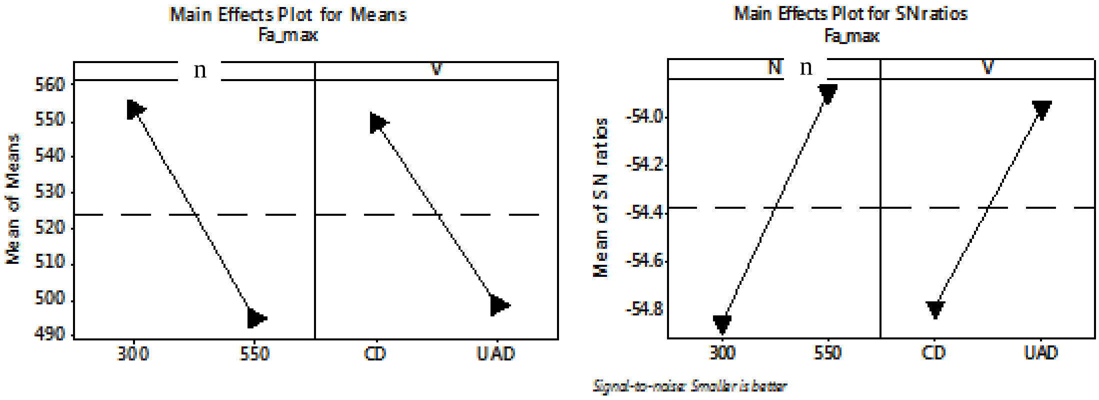

Figure 2. Main effects plot for Mean of F_a_max (left) and for Mean of S/N ratios (right)

Table 5. Analysis of Variance for Signal to Noise Ratios (for T_max)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
n	1	5.4268	5.42678	5.42678	1.01	0.498	50.0
V	1	0.0783	0.07831	0.07831	0.01	0.923	0.7
Error	1	5.3647	5.36467	5.36467			49.3
Total	3	10.8698					100.0

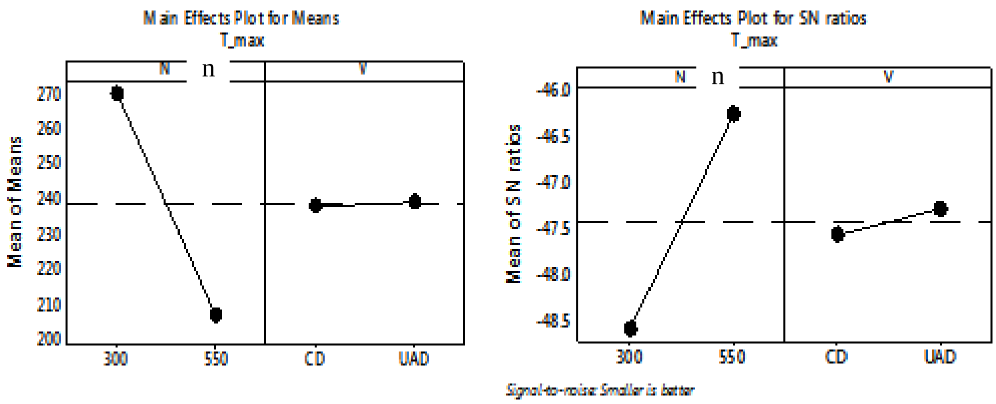

Figure 3. Main effects plot for Mean of T_max (left) and for Mean of S/N ratios (right)

V. ANALYSIS OF WORK DONE

The same as above, S/N ratios were calculated with Taguchi method for work done using smaller the better characteristic and S/N ratios are shown on the Table 6. In the ANOVA, at a confidence level of 99.8%, the experimental results and the Taguchi S/N ratios were evaluated as shown in Table 6. ANOVA also determined the contribution of individual parameters on the minimum work done consumed. According to the

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ANOVA for S/N ratio of work done, the spindle speed shows more contribution of 93.6%. Herein, the error was found as 0.1%.
Figure 4 shows mean of work done (left figure) and mean of S/N ratios to the levels of drilling parameters (right figure). As can be seen, the suitable levels of drilling parameters are 550 rpm spindle speed and UAD process for minimum value of work done. It can be said that, UAD process and the higher spindle speed consume less energy than CD process and lower cutting speed, respectively.

Table 6. Analysis of Variance for Signal to Noise Ratios (for work done)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
n	1	10.9037	10.9037	10.9037	709.39	0.024	93.6
V	1	0.7339	0.7339	0.7339	47.75	0.091	6.3
Error	1	0.0154	0.0154	0.0154			0.1
Total	3	11.6529					100.0

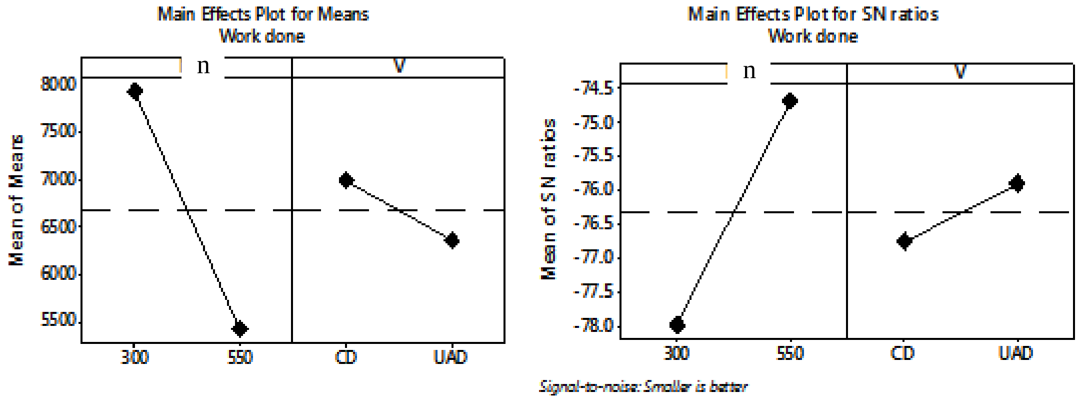

Figure 4. Main effects plot for Mean of Work done (left) and for Mean of S/N ratios (right)

VI. CONCLUSION

In this work, eight experiments were performed with two levels of drilling parameters on AISI 304 stainless steel. The experiments were designed according to Taguchi orthogonal array of L8 and experiments were performed with two levels of the cutting parameters, including cutting speed and drilling methods (i.e. CD and UAD). The influences of drilling parameters were analysed by collecting thrust force and drilling torque during process, then calculating the work done. Analysis of Variance methods were used to identify significant drilling parameters affecting the thrust force, drilling torque and work done. The experimental results revealed that:

- Thrust force, drilling torque and work done are more affected by drilling speed.
- With the same drilling speed, ultrasonic assisted drilling process constitutes smaller of thrust force, drilling torque and work done than those of conventional drilling.

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