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Comparison of Deep Drilling Efficiency between Ultrasonic Vibration-Assisted Drilling and Conventional Drilling based on Specific Energy Consumption

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Abstract

Deep hole drilling remains a persistent challenge in both research and industry due to high friction and inadequate chip evacuation, which leads to inefficiencies. This study evaluates the efficiency of deep drilling using ultrasonic vibration-assisted drilling (UAD) by comparing it with conventional drilling (CD), with specific energy consumption (SEC) as the primary metric derived from torque measurements. Here, SEC is defined as an accumulated function integrating energy consumption over the entire drilling process, mitigating non-linear and stochastic variations common in deep drilling. Experiments were conducted on Al-6061 aluminum alloy under continuous dry drilling conditions, with variations in spindle speed, feed rate, and hole diameter. The results demonstrate that UAD significantly improves drilling efficiency compared to CD. Specifically, the SEC value for UAD was approximately 21.44% to 77.74% lower than that for CD across all experimental conditions. Moreover, with optimized parameters, UAD achieved a 25% increase in material removal rate (MRR) and a 33.4% reduction in SEC compared to CD. These findings highlight UAD's potential to enhance deep hole drilling efficiency, offering promising applications for industrial machining processes.

Keywords: Ultrasonic vibration-assisted drilling, deep hole drilling, specific energy consumption, material removal rate, Al-6061 aluminum alloy.

1. Introduction

The machining industry is a major energy consumer, responsible for approximately 33% of total industrial energy use and contributing to nearly 38% of global CO_2 emissions [1]. Within this sector, machining processes account for up to 90% of energy consumption, yet only 10-15% of that energy is effectively utilized for actual material removal, and the remainder is lost to system inefficiencies [2]. Among various metal-cutting operations, drilling alone constitutes about 33% of the total volume, and more than 50% of machining activities in the aerospace and automotive industries [3]. As a result, improving the energy efficiency of drilling operations has become a critical priority for sustainable manufacturing.

Twist drills remain the most widely used tool in drilling operations, accounting for about 70% of tools employed in deep-hole machining applications [4]. In the aerospace sector, where millions of holes are required for riveting and bolting during aircraft assembly, drilling is indispensable. However, conventional drilling methods are still characterized by low energy efficiency, with significant energy losses occurring due to high friction and inefficient chip evacuation, particularly in deep-hole applications.

Aluminum alloys, especially Al-6061, are extensively used in aerospace, automotive, defense, and civil engineering industries due to their lightweight, high specific strength, corrosion resistance, and excellent machinability. In aerospace applications, aluminum alloys constitute up to 80% of an aircraft's structural mass, and Al-6061 is commonly selected for critical components such as wings, frames, and fuselage sections. Despite these favorable properties, Al-6061 presents considerable challenges during drilling. The material tends to form long, thick chips, which hinder evacuation, increase friction, degrade hole quality, and elevate the risk of tool breakage [5]. Under dry machining conditions, the lack of coolant exacerbates chip adhesion, leading to accelerated tool wear and failure [6].

To address these challenges, various strategies such as minimum quantity lubrication (MQL) and cryogenic cooling have been explored. However, their effectiveness remains limited, particularly in maintaining energy efficiency during deep-hole drilling. More recently, ultrasonic vibration-assisted drilling (UAD) has emerged as a promising solution, especially for difficult-to-machine materials. By superimposing high-frequency axial vibrations onto the cutting process, UAD transforms the continuous cutting of conventional

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drilling (CD) into an intermittent process, which effectively breaks chips into smaller segments, reduces friction, enhances chip evacuation, and improves hole quality and tool life [7]. In dry deep-hole drilling of Al-6061 with a length-to-diameter (*L/D*) ratio of 13.3, UAD has been shown to reduce the torque required for chip evacuation by up to 33 times compared to CD [8].

Despite its proven mechanical advantages, there remains a significant research gap regarding the energy consumption of UAD in deep-hole drilling. Existing power consumption models-such as Shun Jia's model based on spindle speed, feed rate, and hole diameter [2], or Qi Wang's model accounting for idle, cutting, and auxiliary power [9] - have only been validated on large-diameter holes and low *L/D* ratios. These models often overlook torque-based energy analysis and the role of chip evacuation forces, both of which are critical in deep-hole drilling and have been highlighted in recent literature [10, 11].

This study aims to fill that gap by evaluating specific energy consumption (SEC), a torque-based metric, during deep-hole drilling of Al-6061 aluminum alloy under dry conditions. The experiments compare ultrasonic vibration-assisted drilling with conventional drilling. The experiments focused on three critical parameters: drill diameter (*D*), spindle speed (*n*), and feed rate (*f*), selected due to their significant influence on energy consumption and material removal efficiency. The levels of each factor are presented in Table 1 and Table 2, representing a broad range of industrially relevant operating conditions.

All drilling operations were performed using a V-Turn 410 universal lathe, which provided a stable platform for consistent and repeatable measurements. The workpieces were fabricated from Al-6061-T6 aluminum alloy, selected due to its widespread industrial use and excellent machinability. Each workpiece was a square bar with dimensions of 10 mm × 10 mm × 30 mm, ensuring uniformity across all test runs. High-speed steel (HSS) twist drills (Nachi List 500) were used, with diameters of 3 mm, 4 mm, and 5 mm corresponding to *L/D* ratios of 10, 7.5, and 6, respectively. These tool dimensions were chosen to reflect typical industrial deep drilling applications. For UAD, an ultrasonic transducer operating at 20 kHz and a vibration amplitude of 10 µm imparted axial vibration to the drill. This system was powered by an MPI WG-3000 ultrasonic generator, ensuring stable and consistent vibration throughout the process.

Table 1. Drilling test parameters

Parameters	Levels		
	1	2	3
Spindle speed, *n* (rpm)	1000	1250	1500
Feed rate, *f* (mm/rev)	0.05	0.065	0.085
Drill diameter, *D* (mm)	3 (*L/D* = *10*)	4 (*L/D* = *7.5*)	5 (*L/D* = *6*)

Table 2. Factors with levels in the drilling process (orthogonal array of L27)

No.	*D* (mm)	*n* (rpm)	*f* (mm/rev)	No.	*D* (mm)	*n* (rpm)	*f* (mm/rev)	No.	*D* (mm)	*n* (rpm)	*f* (mm/rev)
1	3	1000	0.05	10	4	1000	0.065	19	5	1000	0.085
2	3	1000	0.05	11	4	1000	0.065	20	5	1000	0.085
3	3	1000	0.05	12	4	1000	0.065	21	5	1000	0.085
4	3	1250	0.065	13	4	1250	0.085	22	5	1250	0.05
5	3	1250	0.065	14	4	1250	0.085	23	5	1250	0.05
6	3	1250	0.065	15	4	1250	0.085	24	5	1250	0.05
7	3	1500	0.085	16	4	1500	0.05	25	5	1500	0.065
8	3	1500	0.085	17	4	1500	0.05	26	5	1500	0.065
9	3	1500	0.085	18	4	1500	0.05	27	5	1500	0.065

2. Materials and Methods

The experimental setup used in this study is shown in Fig. 1, presenting the configuration designed to evaluate the efficiency of ultrasonic vibration-assisted drilling compared to conventional drilling. The research follows a structured methodology based on the Taguchi method, employing an L27 orthogonal array to systematically examine the influence of key drilling parameters. Two distinct sets of experiments were conducted under identical cutting conditions, specifically dry drilling, to isolate the effect of ultrasonic vibration and accurately assess its impact on energy efficiency.

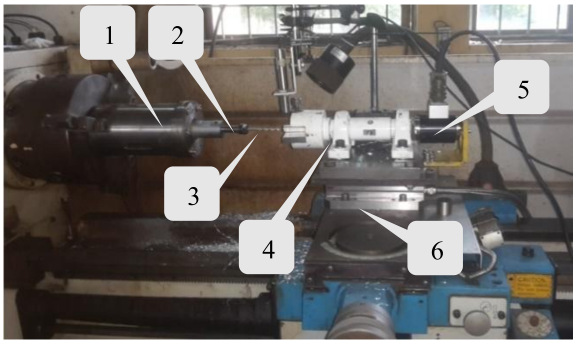


Fig. 1. Experimental equipment
(1) ultrasonic tool holder, (2) drill bit, (3) workpiece, (4) fixture, (5) torque sensor, (6) force sensor

Torque was measured using a PCB-2508-03A sensor, which is critical for assessing energy efficiency since torque correlates directly with power consumption. Data acquisition was carried out using a USB NI-6008 module, enabling real-time recording of torque and associated parameters. The collected data were analyzed using OriginLab and Minitab software.

Power (P) generated by torque (T) at any given time t was calculated using:

$$P(t) = T(t) \, . \, \omega(t) \tag{1}$$

where $\omega(t)$ represents the angular velocity at time t, defined as $\omega = n \cdot 2\pi/60$. The instantaneous energy consumption (W) at each time (t) was determined using:

$$W = P.t = (T.\omega).t \tag{2}$$

Given the dynamic nature of energy consumption during the drilling process, cumulative energy consumption over time was calculated using:

$$W = \int_0^t P(t)\, dt \tag{3}$$

where, t represents the total time required to complete each hole, starting from the initial contact between the cutting tool and the workpiece until the hole is fully drilled.

The *SEC*, a key metric for evaluating the efficiency of the drilling process, was computed using:

$$SEC = \frac{W}{V} \tag{4}$$

where W is the total energy consumed during the drilling process (in Joules), and V represents the volume of material removed (in cubic millimeters).

This comprehensive experimental design and measurement strategy ensures a reliable evaluation of UAD's energy-saving potential, particularly in deep-hole drilling applications where conventional methods are typically inefficient. By systematically varying drilling parameters and capturing real-time torque data, the study aims to provide robust evidence supporting the industrial adoption of UAD in energy-conscious machining environments.

3. Results and Discussion

3.1. Torque Analysis

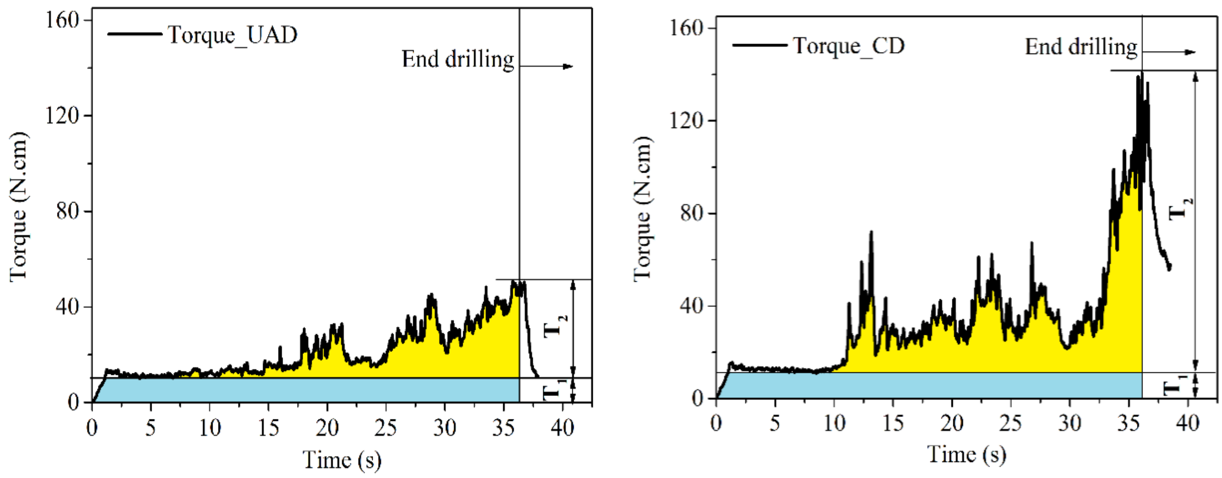
Fig. 2(a) and Fig. 2(b) illustrate the torque profiles during drilling under identical conditions (n = 1000 rpm and f = 0.05 mm/rev) for both UAD and CD. In deep-hole drilling, the total torque comprises two main components: cutting torque (T_1) and chip removal torque (T_2). T_1, generated at the tool's cutting edge, remains relatively constant regardless of drilling depth, as it is essential for maintaining the cutting action. In contrast, T_2 results from the friction between the chips and the borehole wall, and it increases with drilling depth. In CD, this increase is particularly pronounced due to the stick-slip effect, which occurs when chips accumulate and clog the hole, leading to significant torque fluctuations.

As shown in Fig. 2, the T_2 component in UAD is consistently lower than that in CD, indicating reduced friction and consequently lower energy consumption. This reduction in T_2 directly contributes to the lower total energy usage observed in UAD, as further confirmed by the SEC data. UAD's ability to maintain lower T_2 values highlights its effectiveness in reducing the energy required for chip evacuation, thereby improving the overall efficiency of the drilling process.

3.2. Energy Consumption Breakdown

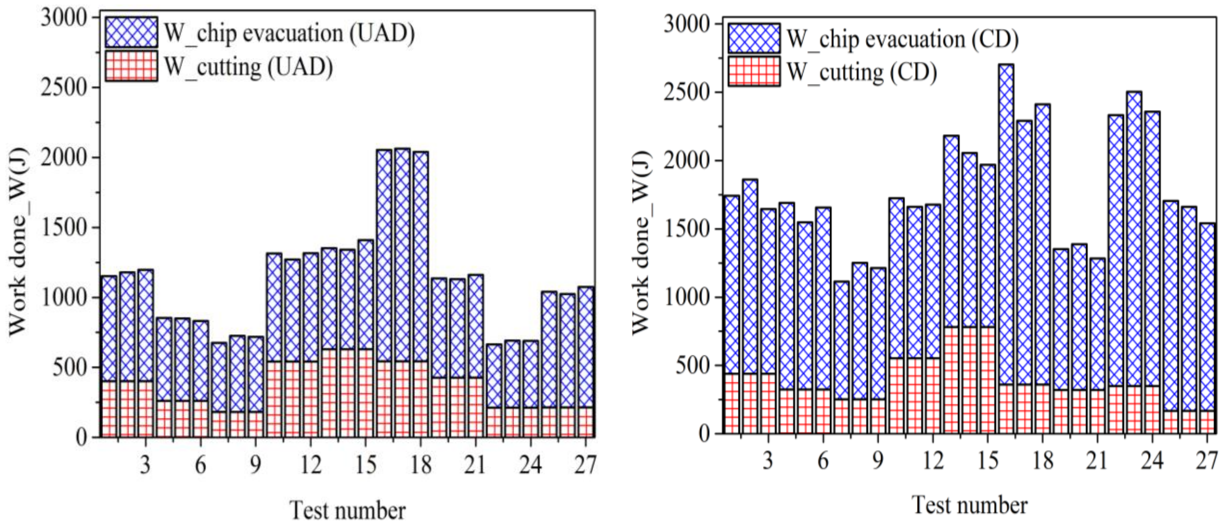
Fig. 3 provides a detailed comparison of the total energy consumption during the drilling process for both UAD and CD. For each drilled hole, the total energy consumption (W) can be decomposed into two components: the energy associated with cutting torque (W_{cut}) and the energy associated with chip removal torque (W_{chip}). The relationship is expressed as:

$$W = W_{cut} + W_{chip} \tag{5}$$



(a) (b)

Fig. 2. Torque measured while drilling at the same cutting conditions (n = 1000 rpm and f = 0.05 mm/rev): (a) UAD and (b) CD



(a) (b)

Fig. 3. Total energy consumption during the drilling process: (a) UAD and (b) CD

To assess the relative contributions of each component, two energy efficiency ratios are defined:

$$W_k = \frac{W_{cut}}{W} \quad or \quad W_k' = \frac{W_{chip}}{W} \tag{6}$$

where, W_k represents the proportion of energy used for effective cutting, while W_k' reflects the proportion of energy consumed for chip evacuation. A higher W_k or lower W_k' indicates a more energy-efficient drilling process.

As shown in Fig. 3 and Table 3, the W_k' ratio is notably higher in CD, with 15 out of 27 drilled holes exhibiting values exceeding 70%. In contrast, only 3 out of 27 holes in UAD exceed this threshold. On average, the total energy consumption in CD (1402.6 J) is 1.82 times greater than that of UAD (766.8 J). These results highlight the superior energy efficiency of UAD, primarily due to the influence of ultrasonic vibration, which reduces friction and improves chip evacuation.

Table 3. Experimental results

No.	W_{cut} (CD)	W_{cut} (UAD)	$W_{friction}$ (CD)	$W_{friction}$ (UAD)	W (CD)	W (UAD)	$\%W'_k$ (CD)	$\%W'_k$ (UAD)	SEC (UAD)	SEC (CD)
1	439.746	402.099	862.684	347.304	1302.43	749.403	66.236	46.344	3.534	6.142
2	439.746	402.099	982.194	374.256	1421.94	776.355	69.074	48.207	3.661	6.705
3	439.746	402.099	766.044	393.177	1205.79	795.276	63.530	49.439	3.750	5.686
4	324.279	260.574	1042.141	332.802	1366.42	593.376	76.268	56.086	2.798	6.444
5	324.279	260.574	898.791	328.732	1223.07	589.3055	73.486	55.783	2.779	5.768
6	324.279	260.574	1007.218	310.062	1331.498	570.636	75.646	54.336	2.691	6.279
7	251.816	182.160	610.699	311.399	862.515	493.5588	70.804	63.093	2.327	4.067
8	251.816	182.160	746.962	362.154	998.778	544.3136	74.788	66.534	2.567	4.710
9	251.816	182.160	709.875	354.913	961.691	537.0728	73.815	66.083	2.533	4.535
10	553.481	542.547	617.012	228.714	1170.494	771.261	52.714	29.654	2.046	3.105
11	553.481	542.547	553.759	185.727	1107.24	728.2746	50.013	25.502	1.932	2.937
12	553.481	542.547	570.749	229.865	1124.23	772.4124	50.768	29.759	2.049	2.982
13	782.275	629.813	617.465	91.308	1399.74	721.121	44.113	12.662	1.913	3.713
14	782.275	629.813	489.975	80.865	1272.25	710.678	38.512	11.379	1.885	3.375
15	782.275	629.813	404.565	148.961	1186.84	778.7736	34.088	19.128	2.066	3.148
16	359.891	544.319	1983.249	965.491	2343.14	1509.81	84.641	63.948	4.005	6.215
17	359.891	544.319	1571.849	973.201	1931.74	1517.52	81.370	64.131	4.025	5.124
18	359.891	544.319	1691.059	949.767	2050.95	1494.087	82.452	63.568	3.963	5.440
19	321.265	427.342	709.295	280.785	1030.56	708.127	68.826	39.652	1.202	1.750
20	321.265	427.342	744.735	276.104	1066	703.446	69.863	39.250	1.194	1.810
21	321.265	427.342	641.774	306.026	963.039	733.368	66.641	41.729	1.245	1.635
22	350.034	212.230	1632.716	239.845	1982.75	452.075	82.346	53.054	0.767	3.366
23	350.034	212.230	1804.046	267.318	2154.08	479.548	83.750	55.744	0.814	3.657
24	350.034	212.230	1658.006	264.884	2008.04	477.1134	82.568	55.518	0.810	3.409
25	167.439	214.007	1369.951	612.798	1537.39	826.805	89.109	74.116	1.404	2.610
26	167.439	214.007	1326.991	595.561	1494.43	809.568	88.796	73.565	1.374	2.537
27	167.439	214.007	1205.541	647.553	1372.98	861.56	87.805	75.161	1.463	2.331

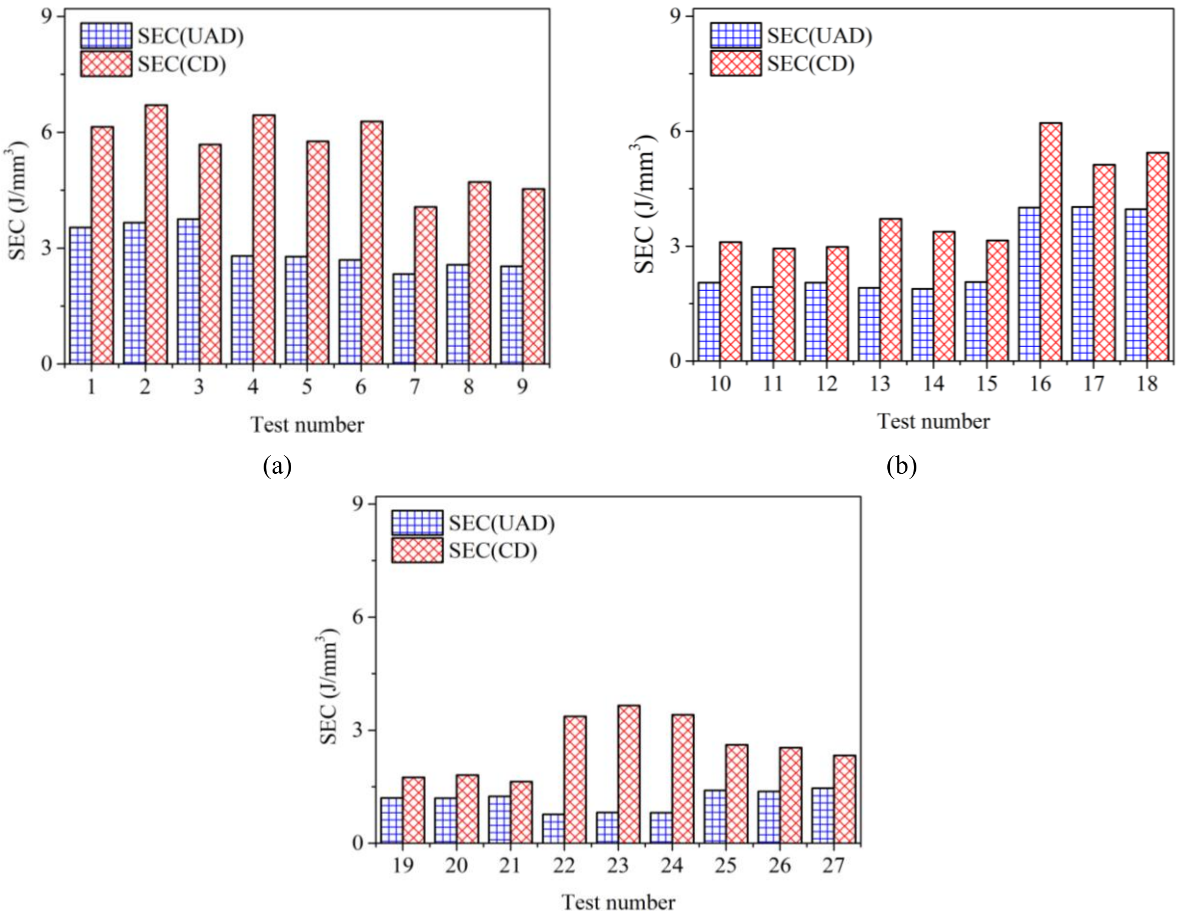


Fig. 4. Statistical results of SEC values for each drill hole diameter under both UAD and CD: (a) D = 3 mm, (b) D = 4 mm, and (c) D = 5 mm

3.3. Specific Energy Consumption Analysis

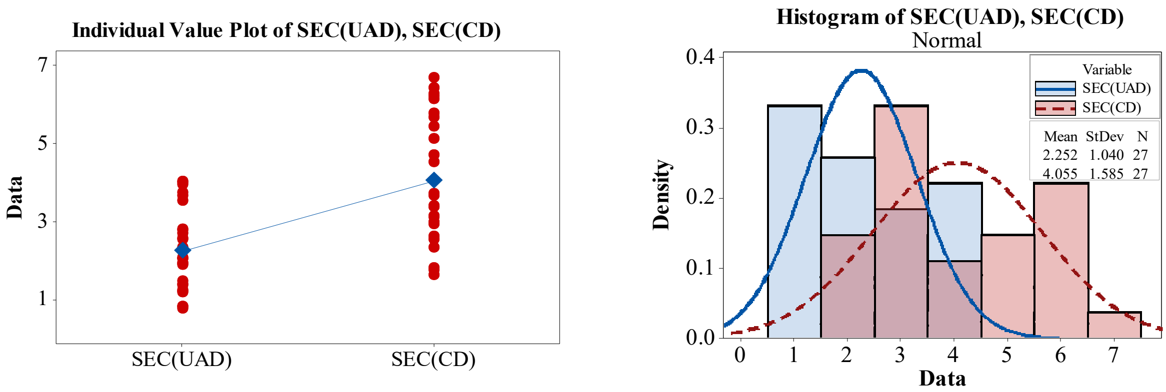
Specific energy consumption is a critical metric for assessing the energy efficiency of drilling processes. Fig. 4 presents a statistical comparison of SEC values for both UAD and CD. The data indicate that SEC generally decreases as the drill hole diameter increases in both methods. However, UAD exhibits a more pronounced reduction in SEC, with decreases ranging from 21.44% to 77.74% compared to CD, underscoring its superior energy utilization efficiency.

The paired *t*-test results, shown in Table 4 and Fig. 5, further confirm the statistically significant difference between the SEC values of UAD and CD. The mean SEC for CD is 4.055, nearly double that of UAD at 2.252. The analysis yields a *t*-value of 10.04 and a *p*-value of 0.000, indicating a highly significant difference between the two drilling approaches at the 95% confidence level.

The reduced SEC in UAD is primarily attributed to the ability of ultrasonic vibration to minimize friction both between chips and the tool's flutes and between chips and the borehole wall. This reduction in friction leads to a lower chip removal torque component, thereby decreasing the overall energy required during the drilling process.

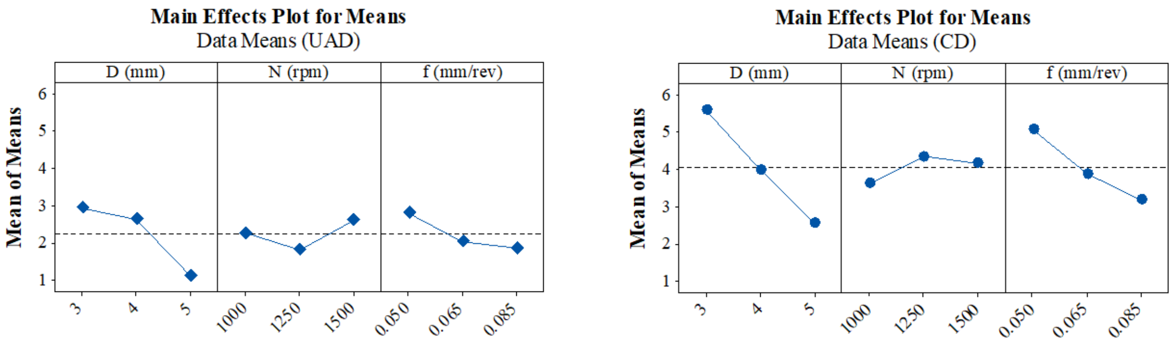
Table 4. Paired T-Test and Confidence Interval (CI) for SEC(UAD) and SEC(CD)

Descriptive Statistics				
Sample	N	Mean	StDev	SE Mean
SEC(UAD)	27	2.252	1.040	0.200
SEC(CD)	27	4.055	1.585	0.305
Estimation for Paired Difference				
Mean	StDev	SE Mean	95% CI for μ_difference	
-1.803	0.933	0.180	(-2.172, -1.434)	
μ_difference: mean of (SEC(UAD) - SEC(CD)) Test				
Null hypothesis		H₀: μ_difference = 0		
Alternative hypothesis		H₁: μ_difference ≠ 0		
T-Value		*P*-Value		
-10.04		0.000		



(a) (b)

Fig. 5. Results of the paired comparison (Paired T-Test) with a 95% confidence interval for the two datasets: SEC (UAD) and SEC (CD)



(a) (b)

Fig. 6. Impact of drilling parameters on the average SEC value in UAD (a) and CD (b)

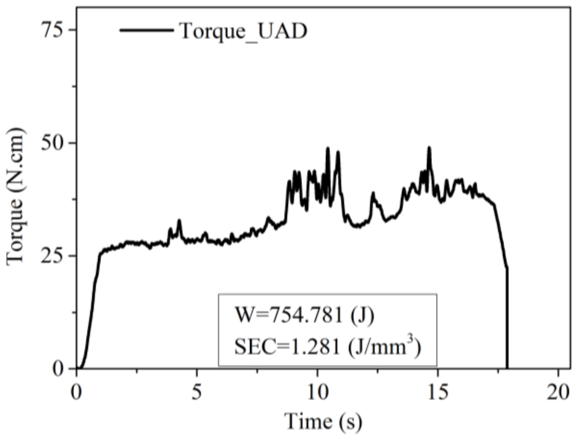
3.4. Influence of Drilling Parameters on Energy Consumption

Fig. 6 illustrates the influence of drilling parameters on the average SEC values for both UAD and CD. The analysis reveals that SEC tends to decrease with increasing drill diameter, feed rate, and spindle speed. This observation contrasts with prior studies, such as GurRaj Singh's work on drilling Al-6061 [12], which reported that larger drill diameters increase cutting force and power consumption. In the present study, however, the observed reduction in SEC with larger diameters is likely attributed to lower length-to-diameter (*L/D*) ratios, suggesting that SEC is more strongly correlated with drilling depth than diameter alone.

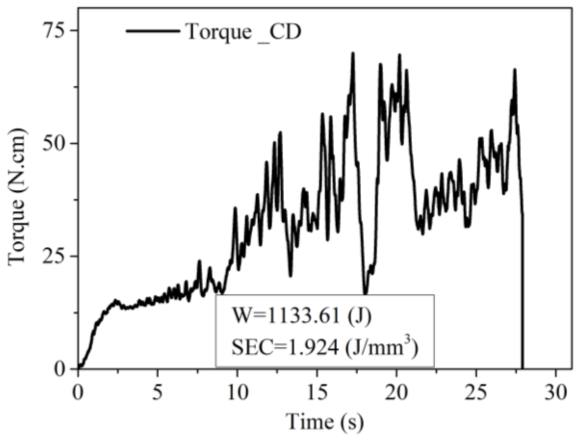
The decrease in SEC at higher feed rates is primarily due to shorter machining times, which reduce the duration of tool–workpiece interaction and facilitate more effective chip evacuation. Although spindle speed exerts the least influence on SEC among the three parameters, higher spindle speeds can still lead to increased energy consumption as a result of elevated cutting temperatures and accelerated tool wear. This trend contradicts some previous studies, which observed higher SEC with increased diameter. However, in our study, larger drill diameters correspond to lower *L/D* ratios, resulting in reduced chip evacuation resistance. Furthermore, the use of UAD improves chip fragmentation and heat dissipation, making the process more efficient at larger diameters.

3.5. Verification of Optimal Drilling Conditions

To validate the optimal conditions for energy-efficient drilling, the analysis presented in Fig. 6 was used to identify the cutting parameters that yielded the lowest specific energy consumption for each drilling method. Based on this analysis, the optimal conditions were determined as D = 5 mm, n = 1250 rpm, and f = 0.085 mm/rev for UAD; and D = 5 mm, n = 1000 rpm, and f = 0.085 mm/rev for CD. Under these respective conditions, UAD achieved a 25% increase in material removal rate (MRR) while simultaneously reducing SEC by 33.4% compared to CD. This performance was confirmed by calculating the drilling time with an actual hole depth of 30 mm, which resulted in approximately 16.94 seconds for UAD and 21.18 seconds for CD. These results demonstrate the superior energy efficiency and productivity of UAD in the deep drilling of Al-6061, underscoring its potential as a viable and advanced alternative to CD techniques for the sustainable machining of aluminum alloys.



(a)



(b)

Fig. 7. Energy efficiency comparison: (a) UAD, (b) CD

4. Conclusion

This study demonstrates the effectiveness of UAD in enhancing the performance of deep-hole drilling in Al-6061 aluminum alloy. A novel specific energy consumption model was developed using real-time torque measurements to capture cumulative energy consumption over time. By distinguishing between cutting torque and chip evacuation torque, the model provides a more accurate and process-sensitive evaluation of drilling energy use compared with previous approaches.

Experimental results confirmed that UAD significantly improves energy efficiency relative to CD. Across all tested conditions, UAD achieved reductions in SEC ranging from 21.44% to 77.74%. Under optimized parameters, UAD also delivered a 25% increase in material removal rate and a 33.4% decrease in SEC compared to CD. These improvements are primarily attributed to reduced friction and enhanced chip evacuation enabled by ultrasonic vibration.

Beyond energy savings, UAD contributes to better machining outcomes by improving productivity, enhancing surface finish, and extending tool life. Collectively, these advantages establish UAD as a superior alternative to CD, with strong potential for industrial adoption where sustainability, precision, and tool longevity are critical. This research not only advances the understanding of energy consumption in deep drilling but also provides a solid foundation for future studies aimed at optimizing UAD for broader applications in sustainable manufacturing.

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Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this article.

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