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Use of Custom Macro Functions (CMFs) and Grey-Taguchi Method for Ultrasonic Vibration-Assisted Small Diameter Deep-Hole Drilling (SDDHD) of Ti-6Al-4V Alloy

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Keywords：custom macro functions, ultrasonic vibration-assisted machining, small diameter deep-hole drilling, multi-quality characteristics, grey-Taguchi method.

ABSTRACT

Small diameter deep-hole drilling (SDDHD) of Ti-6Al-4V alloy has become a subject of concern to many researchers due to its common shortcomings such as poor hole quality, high unit energy consumption, short tool life, and high processing cost. When writing processing codes for parts on CNC machine tools, using the custom macro function (CMF) can reduce the overall programming time and cost compared with CAD/CAM systems. For different process applications, many studies use non-traditional machining (NTM) to shorten the machining cycle of difficult-to-cut materials (DCM). Ultrasonic vibration-assisted machining (UVAM) is an effective method to achieve this goal. The Grey-Taguchi method is often used to solve the problems of multi-quality characteristics (MQCs) optimization. Therefore, this study combines CMFs, Grey-Taguchi method and UVAM to optimize the MQCs (thrust force (F) and surface roughness (R)) of SDDHD Ti-6Al-4V alloy. The experimental results show that specific processing parameters (spindle speed (A), feed rate (B), pecking-depth (C) and ultrasonic current (D)) have the significant effect on the optimal MQCs for ultrasonic vibration-assisted SDDHD in Ti-6Al-4V alloy. B and D are the most important processing parameters of MQC, with contribution rates (*P*) of 42.89% and 28.41%, respectively. Moreover, CMFs can obviously reduce CNC programming time for the 2nd and subsequent parts in SDDHD of Ti-6Al-4V alloy by 90% compared to CAD/CAM systems.

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INTRODUCTION

Small diameter deep-hole drilling (SDDHD) is widely used in the manufacturing of micro-parts in energy, automotive, aviation, mold, biomedicine and other industries, which accounts for more than 40% of the entire hole-making process (Zhang et al., 2022). SDDHD methods include electrical discharge machining, ultrasonic machining, laser beam machining, electrochemical machining and mechanical drilling. However, mechanical drilling has the processing advantages of short processing time, good drilling quality, and low manufacturing cost, and is currently widely used in SDDHD. Peck-drilling using intermittent feed is the most effective method for SDDHD with machining parameters including spindle speed, feed rate, pecking-depth, tool material and geometry, cooling and lubrication. During the SDDHD process, friction, chatter, deflection and material removal between the drill bit and the workpiece increase the difficulty of chip removal and hole surface roughness (R), and reduce tool life and hole dimensional accuracy. Therefore, SDDHD without ultrasonic vibration assistance can no longer meet the accuracy and efficiency requirements for deep-hole processing of advanced materials.

Many researchers have explored the impact of various process parameters on SDDHD performance. Kim et al. (2009) introduced the LabVIEW monitoring system and determined that the appropriate one-step feed length (OSFL) for stable processing in deep micro-hole drilling of steel is approximately one-tenth of the tool diameter. Aized and Amjad (2013) proved that the spindle speed and feed rate have a great influence on the drilling quality. Small pecks can improve process quality and prevent excessive tool wear by using coolant and destroying chips. Khan et al. (2017) found that maintaining the minimum spindle speed and feed rate, and increasing the peck depth from 3 mm to 5 mm will shorten the tool life by about 18%, and the maximum contribution rate of feed rate is approximately 50%. Zhang et al. (2020) used the particle swarm algorithm to obtain optimized quality characteristics (processing time, tool wear and drilling force) of peck deep-hole drilling under given processing conditions (spindle speed and feed rate), and effectively reduced its energy consumption. Iqbal et al. (2021) found that micro-lubrication using throttling and evaporating cryogenic fluids has better drilling quality for carbon fiber-reinforced plastic (CFRP) than dry drilling and two cryogenic coolants (compressed carbon dioxide and liquid nitrogen). Wang et al. (2023) found that longitudinal-torsional ultrasonic vibration-assisted pecking drilling can control the Ti chip morphology and help improve the processing quality of the hole. Chen et al. (2024) confirmed that the geometry of the step drill can remove most of the chips and cutting heat by pecking the Ti layer, which is beneficial to reducing thermal damage to CFRP. Since SDDHD uses a pecking method to remove material, studying the impact of its process parameters on various quality responses of the workpiece after processing is crucial to improving operating efficiency and reducing manufacturing costs.

Ti-6Al-4V alloy features high strength, high rigidity, excellent corrosion and oxidation resistance, high creep strength and fatigue, chemical inertness and good processability and stability. However, Ti-6Al-4V alloy has the disadvantages of work hardening, poor thermal conductivity, chemical reaction with tools at high temperatures, jagged chips and low Young's coefficient. Currently, Ti-6Al-4V alloy is used to manufacture assembled body parts with a diameter of less than 1 mm in the aerospace industry and is one of the DCMs. When a small-diameter drill bit is used for drilling at a high rotational speed, the drilling thrust (F) will be too large, and may even cause the drill bit to fail or break. Traditional drilling (TD) of Ti-6Al-4V alloy is difficult, so NTM is a more effective solution for DCMs. Ultrasonic vibration-assisted drilling (UVAD) is commonly used in DCM and is a topic that many researchers are interested in exploring. Unlike TD, UVAD applies a vibration amplitude in the feeding direction, so there is intermittent periodic cutting between the drill bit and the workpiece. At this time, the fracture chips generated by ultrasonic vibration are easier to discharge, the processing efficiency is higher, and the surface roughness is lower. For UVAD, vibration frequency and amplitude (current) are the main factors affecting the processing quality and efficiency of workpiece.

UVAM is the most widely adopted NTM technology and offers significant potential for DCM materials. Pujana et al. (2009) noted that using UVAD for Ti-6Al-4V alloy decreases the feed force and increases the processing temperature. Liu et al. (2023) found that ultrasonic peening drilling (UPD) of Ti-6Al-4V alloy reduces surface roughness and increases surface hardness, plastic deformation and residual stress, compared to traditional PD. Li et al. (2017) confirmed that Ti-6Al-4V alloy that is drilled using ultrasonic vibration and plasma electrolytic oxidation involves a grinding force that by 60% less and the surface roughness is 46 % less than that for traditional grinding. Zhang et al. (2018) noted that for ultrasonic vibration assisted high-speed turning of Ti-6Al-4V alloy, surface roughness does not exceed 0.4 μm (Ra). Yang et al. (2019) found that low-frequency ultrasonic drilling of Ti-6Al-4V alloy increases drilling quality and processing efficiency. Shard et al. (2023) found that UVAD of CFRP prevents cracks and delamination and reduces cutting force, torque and surface roughness. Wang et al. (2021) found that micro-hole drilling of 3D-needled Cf/SiC by ultrasonic vibration reduces hole wall roughness and cutting force. As the amplitude decreases, the hole wall and the exit edge of the workpiece feature the best processing quality. Makhdum et al. (2014) found that using a φ3 mm drill bit for UVAD of CFRPs at a feed rate less than 20 mm/min gives good surface roughness, roundness and inhibits delamination. The above experiments prove that UVAM is an effective method to reduce processing damage.

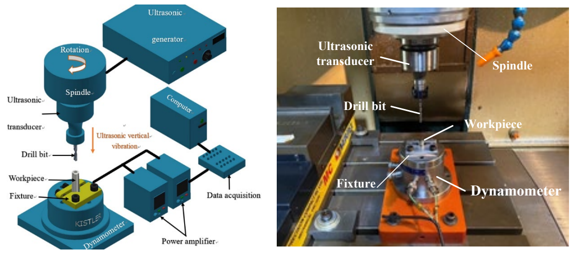
Improving the performance of SDDHD requires a focus on process and energy efficiency, which is a key aspect in this study. CNC parametric coding can be analyzed from the concepts of geometric features and processing conditions of the part (Zhang et al., 2012). By combining high-level programming languages with CNC codes, user-defined fixed cycle instructions are created to perform parameterized repetitive machining of different types of parts (Abbas and Megahed, 2005). G83 is the most commonly used fixed cycle instruction for deep-hole drilling (DHD) in CNC machining centers. The chisel edge of the twist drill has no cutting effect so the feed rate must be decreased when entering or exiting the workpiece, especially for SDDHD. If tools with different geometries and sizes are used in SDDHD, the time and cost for production, testing and analysis of the G83 instruction code of the CNC machining center will also increase. The pecking-depth and feed rate for G83 affect the chip size and shape of DHD, chip crushing and discharge. In CAM coding, the pecking-depth and feed speed for G83 are fixed and cannot be adjusted. A computer programming language for a CNC machining center uses custom macro functions (CMFs) and parameter language to control instructions to establish mathematical algorithms, logic control and conditional and system parameter transfer that require cyclic part processing. When only one or a few geometric features of the design model need to be changed, CMFs can obtain the 2nd and subsequent design codes faster than CAD/CAM software (Rodriguez-Alabanda et al., 2019). Therefore, CMFs can not only reduce the programming time and storage capacity of CNC equipment, but also improve production efficiency. However, programming CMFs are complicated and difficult, and the investigation of CMFs in SDDHD has been notably lacking in published literatures.

Moreover, attaining optimal conditions for improved machining multi-quality characteristics (MQCs) poses a significant challenge. Many researchers have utilized various optimization methods to find and optimize relationships between process parameters and machining MQCs. The Grey-Taguchi method is used to optimize MQCs in many industries. Balaji et al. (2021) used the Grey-Taguchi method and multiple linear regression equations to optimize the multi-quality characteristics for abrasive water jet (AWJ) drilling of SUS 304 using abrasive mixtures. The study found that using an abrasive mixture increases the process performance for AWJ for SUS 304 drilling, compared with a single type of abrasive. Tiwari and Panda (2023) used the Grey-Taguchi method to optimize MQC's for electrochemical discharge machining (ECDM) on glass substrates using two tools (bare copper tools and nickel-plated copper tools) and showed that the optimal parameters for ECDM are an applied voltage of 36 V, a tool feed rate of 110 μm/min and a machining time of one minute for nickel-plated copper tools. Lu et al. (2024) used the Grey-Taguchi method to determine the effect of the quenching and tempering process on the mechanical properties of high-strength low-alloy (HSLA) steel and showed that quenching temperature has the greatest effect on various quality characteristics, followed by tempering temperature, and that quenching time and tempering time have the least effect.

Referring to the above literatures, it can be seen that the investigation of the influence of process parameters (spindle speed, feed speed, peck depth and ultrasonic current) and CMFs on MQCs (F and R) holds significant importance. However, there are few studies on combining the Grey-Taguchi method and CMFs to optimize ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. Therefore, current study addresses this troublesome problem by conducting a meaningful investigation.

EXPERIMENTAL PROCEDURES AND METHOD

To determine the effect of the processing parameters and CMFs for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy, this study used a 15 HP vertical three-axis machining center with ultrasonic vibration (Fair Friend Group, Model: Fv-580) and a control unit (Mitsubishi, Model: MELDAS-64SM). A φ10 mm × 30 mm Ti-6Al-4V alloy round bar was clamped in a vise using a home-made clamp and fixed on the table of a CNC machining center. An ultrasonic driver with a power of 350 W and an ultrasonic tool holder operating at 20 kHz were also used. A piezoelectric dynamometer (Kistler, Model: 9273) was used to measure the thrust force (F) for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. The measured F signal was then sent to a charge amplifier (Kistler, Model: 5011) and stored on a personal computer. The ultrasonic vibration-assisted SDDHD equipment for this study as shown in Fig. 1. A surface roughness meter (Mitutoyo, model: SV-3100H4) was used to measure R. The average R (Ra) of the workpiece's hole was measured at four different positions and each position was measured at an interval of 120°. The sampling length for R is 10.8 mm. For ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy, this experiment used the Taguchi method L_9 (3^4) orthogonal table and cutting oil for cooling. The parameters for ultrasonic vibration-assisted SDDHD include spindle speed (rpm), feed rate (mm/min), pecking-depth (mm) and ultrasonic current (amp), and each parameter has three levels. The diameter of the tungsten carbide drill for this study is φ2 mm, as shown in Table 1. Each set of orthogonal tables was drilled twice. The factors and levels and the orthogonal test table for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy for φ2 mm twist drills are shown in Tables 2 and 3.



(a) (b)

Fig. 1. The (a) schematic diagram and (b) photograph experimental setup of ultrasonic vibration-assisted SDDHD.

Table 1. Drill bit specifications used in this study.

Diameter (mm)	Total Length (mm)	Flute Length (mm)	No. of Flutes	Helix Angle	Lip Angle
φ2	80	30	2	25°	118°

Table 2. The factors and levels for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

Control Parameter	Spindle Speed (rpm)	Feed Rate (mm/min)	Pecking-Depth (mm)	Ultrasonic Current (amp)
Symbol	A	B	C	D
Level 1	1,600	60	0.6	0.40
Level 2	1,800	80	0.8	0.75
Level 3	2,000	100	1.0	1.10

Table 3. The orthogonal test table for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

No.	A (rpm)	B (mm/min)	C (mm)	D (amp)
1	1,600	60	0.6	0.40
2	1,600	80	0.8	0.75
3	1,600	100	1.0	1.10
4	1,800	60	0.8	1.10
5	1,800	80	1.0	0.40
6	1,800	100	0.6	0.75
7	2,000	60	1.0	0.75
8	2,000	80	0.6	1.10
9	2,000	100	0.8	0.40

The Taguchi method can only be used for a single quality characteristic (SQC) (Taguchi et al., 1989; Peace, 1993). The Grey-Taguchi method uses the Taguchi method and grey relational analysis (GRA) for various MQC problems. Manufacturers must determine the processing parameters that give products stable quality and involve the least costs. The Grey relational grade (GRG) measures the degree of similarity or dissimilarity of curves for the system factors, which are obtained by GRA. GRG measures the correlation between factors and MQCs are converted into a SQC. This study determines the effect of F and R on the ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy so there are two smaller-the-best quality characteristics. The Taguchi method can only determine a SQC for an object but if MQCs are optimized one by one for a SQC, there are conflicts and rejections between the quality characteristics of the object. Analysis using engineering experience results in overly subjective or dogmatic thinking so the Grey-Taguchi method is used to solve the problem of conflicting MQCs using GRG. This study uses four steps for the Grey-Taguchi method.

(1) Grey generation: The reference sequence and comparison sequence are defined and data for each quality characteristic is normalized. This study determines the effect of F and the R on the ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy so the equation for measuring the effect of smaller-the-best is used:

$$x_i^* = \frac{\max x_i^{(o)}(k) - x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)} \quad (1)$$

where $i = 1, \cdots, 9$, $k = 1, 2$. $x_i^{(o)}(k)$ is the comparison sequence, x_i^* is the reference sequence, $max.\, x_i^{(o)}(k)$ is $x_i^{(o)}(k)$ the maximum value and $min.\, x_i^{(o)}(k)$ is the minimum value for $x_i^{(o)}(k)$.

(2) Sequence comparison: For local GRA, the comparison sequence is compared with the reference sequence. The reference sequence is the set number of 1. The difference sequence operation equation is used:

$$\Delta_{ij}(k) = x_i(k) - x_j(k) \quad (2)$$

where $x_j(k) = x_i^*(k)$, $x_i(k)$ is the set number of reference sequences. This study uses the smaller-the-best effect measurement, so the value is 1. $x_j(k)$ is the comparison sequence.

(3) Grey relational coefficient (GRC): The GRC is calculated using the difference sequence as $\gamma(x_i(k), x_j(k))$:

$$\gamma(x_i(k), x_j(k)) = \frac{\Delta\min + \delta\Delta\max}{\Delta_{ij}(k) + \delta\Delta\max} \quad (3)$$

where δ is the identification coefficient, which usually has a value of 0.5, Δmin is the minimum value for $\Delta_{ij}(k)$, and Δmax is the maximum value for $\Delta_{ij}(k)$.

(4) Grey relational grade (GRG): The corresponding GRG (Γ) is calculated using the GRC:

$$\Gamma = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_i(k), x_j(k)) \quad (4)$$

where n is the number of quality characteristics, $1/n$ is the weight coefficient, which is calculated as 0.5.

Substituting the GRC in Eq. (3) into Eq. (4) gives the GRG for SQC. The greater the value, the closer is the comprehensive effect of the MQCs for the experimental group to the optimal case. The GRG is then sorted to determine the best combination of factors in the orthogonal table. The Taguchi method is then used to determine the optimal combination factors for MQCs.

RESULTS AND DISCUSSION

Analysis of SQC

The measurement results for F and R after ultrasonic vibration-assisted SDDHD are shown in Table 4. The analysis of variance (ANOVA) results for F and R after ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy are shown in Table 5. In terms of the values for F in Table 5, the four SDDHD parameters are sorted according to their contribution (*P*): C (47.66%), B (21.50%), D (16.56%) and A (14.28%). The optimal SDDHD parameter combination for the required minimum F is $A_1B_3C_3D_1$: that is, A is 1,600 rpm, B is 100 mm/min, C is 1.0 mm, and D is 0.4 amps. However, C has a much higher contribution than the others. If the value of F of 1.0 mm C is greater than 0.6 mm for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy, the drilling quality and efficiency are higher because for a greater value of C, the tool re-engages the workpiece less frequently to reach the desired depth, so there is better stability and less tool wear. For ultrasonic vibration-assisted SDDHD, the increase in B that is associated with C decreases the value of F. A smaller D value results in a smaller amplitude (impact force) so F between the tool and the workpiece is decreased during drilling. A decrease in A ensures the integrity of the tool cutting edge and reduces the drilling F for the workpiece material. In terms of R in Table 5, the four drilling parameters are sorted according to the value of *P*: B (43.32%), D (21.78%), C (21.57%) and A (13.33%). The optimal SDDHD parameter combination for the required minimum value for R is $A_1B_3C_2D_1$: A is 1,600 rpm, B is 100 mm/min, C is 0.8 mm and D is 0.40 amps. The results for the contribution for ultrasonic vibration-assisted SDDHD show that A, B, C and D have the same effect on R and F as they are all of practical importance. However, in terms of the optimal combination of SDDHD parameters for MQCs, it is impossible to determine which process is best for manufacturing so the optimized MQCs are converted into a SQC using the GRG for the Grey-Taguchi method.

Table 4. The measurement results for F and R after ultrasonic vibration-assisted SDDHD.

No.	Peck-drilling conditions				F (N)	S/N ratio (dB)	R (μm)	S/N ratio (dB)
	A (rpm)	B (mm/min)	C (mm)	D (amp)				
1	1,600	60	0.6	0.40	7.40	-17.38	1.73	-4.76
2	1,600	80	0.8	0.75	9.20	-19.28	1.61	-4.14
3	1,600	100	1.0	1.10	9.25	-19.32	1.15	-1.21
4	1,800	60	0.8	1.10	10.40	-20.34	2.20	-6.85
5	1,800	80	1.0	0.40	12.20	-21.73	1.39	-2.86
6	1,800	100	0.6	0.75	8.50	-18.59	1.92	-5.67
7	2,000	60	1.0	0.75	11.20	-20.98	1.38	-2.80
8	2,000	80	0.6	1.10	12.60	-22.01	2.20	-6.85
9	2,000	100	0.8	0.40	6.60	-16.39	1.15	-1.21

Table 5. The analysis of variance (ANOVA) results for F and R after ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

Factor	Level (S/N, dB)			Degree of freedom	Sum of squares	Variance	F-ratio	Percentage of contribution *P* %)
	1	2	3					
F								
A	-3.37*	-5.12	-3.62	2	5.41	2.70	0.86	14.28
B	-4.80	-4.62	-2.70*	2	8.14	4.07	1.30	21.50
C	-5.76	-4.07	-2.29*	2	18.04	9.02	2.88	47.66
D	-2.95*	-4.20	-4.97	2	6.27	3.13		16.56
Total				8	37.86			100
R								
A	-18.66*	-20.22	-19.79	2	3.89	1.95	0.61	13.33
B	-19.57	-21.00	-18.10*	2	12.64	6.32	1.99	43.32
C	-19.33	-18.67*	-20.68	2	6.29	3.15	0.99	21.57
D	-18.50*	-19.62	-20.56	2	6.36	3.18		21.78
Total				8	29.18			100

*Optimum level

Analysis of MQCs

The GRG and ranking for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy are shown in Table 6. The GRG for No. 9 ($A_3B_3C_2D_1$) is the greatest for all experiments. A greater value for the means better combines MQCs. The equation for the GRG for the larger-the-better is written as

$$\eta_i = -10\log(1/y_i^2) \quad (5)$$

where η_i is the S/N ratio and y_i is the GRG. The S/N ratio for the 9 components is calculated using Eq. (5), as shown in Table 7.

Table 6. The GRG and ranking for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

No.	F (N)	R (μm)	GRG	Rank
1	7.40	1.73	0.6323	3
2	9.20	1.61	0.5344	5
3	9.25	1.15	0.7655	2
4	10.40	2.20	0.3873	8
5	12.20	1.39	0.5176	6
6	8.50	1.92	0.5088	7
7	11.20	1.38	0.5451	4
8	12.60	2.20	0.3333	9
9	6.60	1.15	1.0000	1

Table 7. The S/N ratio of the 9 components.

No.	y_i	η_i (dB)
1	0.6323	-3.9815
2	0.5344	-5.4427
3	0.7655	-2.3211
4	0.3873	-8.2391
5	0.5176	-5.7201
6	0.5088	-5.8691
7	0.5451	-5.2705
8	0.3333	-9.5433
9	1.0000	0.0000

The ANOVA results for GRG for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy are shown in Table 8. The four SDDHD parameters are sorted according to the value of *P*: B (42.89%), D (28.41%), A (16.90%) and C (11.80%). The optimal SDDHD parameter combination for the combined MQCs is $A_1B_3C_3D_1$: A is 1,600 rpm, B is 100 mm/min, C is 1.0 mm, and D is 0.40 amps. The effect of A, B, C and D on the MQCs for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy is still of practical importance. Experience shows that D directly affects the amplitude output for UVAD. But for UVAD, its main role is to produce periodic intermittent separation between the tool and the workpiece. Figs. 2(a) and 2(b) respectively show cross-sections of No. 8 and No. 9 workpieces. In Fig. 2(a), there is obvious adhesion on the hole wall side of No. 8 workpiece (red circle), which may be caused by B and D on the φ2 mm drill bit during ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. It highlights the complexity of the interaction between tool and material when performing SDDHD with ultrasonic vibration-assisted. However, the friction and heat generated by this tool causes chips to stick to the workpiece. Chips do not adhere to the hole wall side of the No. 9 workpiece in Fig. 2(b).

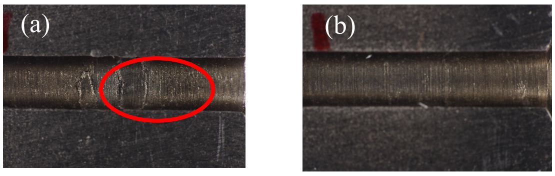


Fig. 2. Cross-section of (a) No. 8 and (b) No. 9 workpieces.

A comparison of the experimental results for No. 9 ($A_3B_3C_2D_1$) and the optimal ($A_1B_3C_3D_1$) SDDHD parameters is shown in Table 9. The MQCs for SDDHD are improved using the Grey-Taguchi method. The value of F is decreased from 6.60 to 6.46 N and the value of R is decreased from 1.15 to 1.10 μm. A decrease in the value of A decreases the amount of frictional heat so the values of F and R are significantly decreased. An increase in the value of C decreases the degree to which the tool re-engages the workpiece to reach the desired depth, which increases stability and decreases tool wear. The results of the confirmation test in Table 9 show that the respective values for F and R for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy are 2.12% and 4.35% less.

Table 8. The ANOVA results for GRG for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

Factor	Level (S/N ratio)			Degree of freedom	Sum of squares	Variance	F-ratio	Percentage of contribution *P* (%)
	1	2	3					
A	-3.9151*	-6.6094	-4.9379	2	11.10	5.55	0.59	16.90
B	-5.8304	-6.9020	-2.7301*	2	28.17	14.08	1.51	42.89
C	-6.4646	-4.5606	-4.4372*	2	7.75	3.88	0.42	11.80
D	-3.2339*	-5.5274	-6.7011	2	18.66	9.33		28.41
Total				8	65.68			100

Table 9. Results of the confirmation test for MQCs using the initial and the optimal process parameters.

Processing parameters	Quality characteristics	
	F (N)	R (μm)
Initial ($A_3B_3C_2D_1$)	6.60	1.15
Optimal ($A_1B_3C_3D_1$)	6.46	1.10
Improvement ratio (%)	2.12	4.35

Analysis of CMFs

In terms of CNC programs for workpieces, CMFs are used to conceptualize and parameterize geometric models. However, in the graphical environment of the CAD/CAM system, programming is easier if a three-dimensional part model is used. Table 10 shows the CMF program for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy for this study. To prevent the φ2 mm twist drill from breaking at the entrance and exit of the drilling workpiece, this study divides the length of the entire SDDHD into an entrance length of 3 mm, a normal length of 24 mm and an exit length of 3 mm. The processing parameters (feed rate, spindle speed and pecking-depth) for the three different drilling lengths can be adjusted. The difference between this adjustable processing parameter setting and G83 is that CMFs programming can use conditional transfer statement (IF) to achieve it. Table 11 shows the results for testing and analysis for ultrasonic vibration-assisted SDDHD of titanium alloy using different CNC codes with CMFs and Mastercam software. The CMFs requires more time to develop a parametric CNC program for SDDHD than Mastercam software. But for solving a 2nd or more subsequent identical situations, the programming cost for CMFs is significantly cheaper.

The CAD/CAM system easily determines the simulation tool-path program in the graphical interface using a post-processing program. The results in Table 11 show that CMFs uses more characters (578.8%) and occupies more CNC memory (5.6%) after post-processing than a CAD/CAM system. The most significant effect of using CMFs for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloys is that is a new design requires different hole positions, pecking-depths, spindle speeds or feed rates. It is faster to reprocess a CNC program than a CAD/CAM system because of a CAD/CAM system is used for a new design or change some insignificant design conditions. The usual workflow must be repeated from beginning to end. CMFs can perform some specific operations of CNC processes. This specific operation usually consists of one or several CMFs in the entire CNC process. Therefore, the programming of CMFs is very suited to work systems that use group-technology because programming time and cost are significantly reduced and the machine settings for a series of parts that is grouped in a specific CNC manufacturing cell are simpler.

Table 10. The CMF program of ultrasonic vibration-assisted SDDHD Ti-6Al-4V alloy.

(*PARAMETERS);	(*MAIN PROGRAM);	G00 G54 G90 X0 Y0;	#14=#14-#8;
#1=1.(R);	G40 G49 G80 G17 G21;	G43 Z50. H03;	G00 Z#1;
#2=10.(Z_END_HIGHT);	M98 H8888 (HOME);	G01 Z5.F2000;	G01 Z#15 F2000;
#3=0.6.(Q1);	M98 H300	Z#1 F700;	G01 Z#14 F#7;
#4=89(Q1_FEED);	(2MM_DRILLING);	N301;	GOTO303;
#5=3.(Q1_Z_HIGHT);	M30;	G01 Z#12 F#4;	N304;
#6=0.8.(Q2);		G00 Z#1;	G00 Z#1;
#7=100(Q2_FEED);	(*HOME);	G04 P500;	G04 P500;
#8=24.(Q2_Z_HIGHT);	N8888;	G01 Z#13 F2000;	N305;
#9=0.6.(Q3);	M05;	IF[#12 LE-#5] GOTO302;	G01 Z#15 F2000;
#10=89(Q3_FEED);	M09;	#12=#12-#3;	G01 Z#16 F#10;
#11=3.(Q3_Z_HIGHT);	G91 G28 Z0;	GOTO301;	IF[#16 LE-#2] GOTO306;
#30=2000;	G91 G28 X0 Y0;	N302;	#16=#16-#9;
	M99;	G00 Z#1;	G00 Z#1;
(*ALCULATED);	%		G04 P500;
#12=#1-#3;		G01 Z#13;	GOTO305;
#13=#12+1.5;	(*2MM_DRILLING);	G01 Z#14 F#7;	N306;
#14=#12-#6;	N300;	N303;	G00 Z#1;
#15=#14+1.5;	T03 M06;	G00 Z#1;	Z50.;
#16=#15-#9;	S#30 M03;	G04 P500;	M99;
#17=#16+1.5;	M08;	IF[#14 LE-#8] GOTO304;	

Table 11. Comparison of results by the different programming methods.

Programming method	Model/Design preparation time (min)	Programming time (min)	Code size (char)	Memory (Kbytes)	Programming time for a 2nd work (min)
Mastercam 2018	15	2.0	118	18	2.0
CMFs	40	0.5	801	19	0.2

CONCLUSIONS

SDDHD is widely used for the manufacturing of parts that are made of DCMs. This study determines the effect of processing parameters on MQCs using the Grey-Taguchi method for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. SDDHD uses new technologies to give increased processing efficiency and quality and CMFs increase the flexibility and versatility of CNC programming. The results of this study allow the following conclusions to be drawn:

(1) In terms of SQC, A, B, C and D have a significant effect on F and R for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. Using appropriate processing parameters has a positive effect on the cutting efficiency and quality characteristic for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

(2) In terms of MQCs, B and D are the two major processing parameters that affect ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. The respective *P* values of B and D are 42.89% and 28.41%. A greater value for B and a smaller value for D increases the MQCs for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy.

(3) The Grey-Taguchi method produces significant improvements on MQCs for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy. The optimal condition ($A_1B_3C_3D_1$) for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy is A at 1,600 rpm, B at 100 mm/min., C at 1.0 mm and D at 0.40 amps. The result of the confirmation test shows that the respective values for F and R for ultrasonic vibration-assisted SDDHD of Ti-6Al-4V alloy is reduced by approximately 2.12% and 4.35%, respectively.

(4) CMFs is the most closed and conservative parametric programming technology for a CNC machining center. Using CMFs for CNC programming of SDDHD significantly reduces the programming time and cost for the 2nd and subsequent part design issues.

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REFERENCES

Abbas, A.T., and Megahed, S.M., “A General Algorithm for Drilling Holes Lying in A Matrix.” *Robot. Comput Integr. Manuf.*, Vol. 21, pp. 235-239 (2005).

Aized, T., and Amjad, M., “Quality Improvement of Deep-hole Drilling Process of AISI D_2.” *Inter. J. Adv. Manuf. Technol.,* Vol. 69, pp. 2493-2503 (2013).

Balaji, K., Siva Kumar, M., and Yuvaraj, N., “Multi Objective Taguchi-grey Relational Analysis and Krill Herd Algorithm Approaches to Investigate the Parametric Optimization in Abrasive Water Jet Drilling of Stainless Steel.” *Appl. Soft. Comput.,* Vol. 102, pp. 107075 (2021).

Chen, C., Zhao, Q., Wang, A., Shi, Z., Yang, Y., and Bao, Y., “Experimental Study on Step Drill Geometry and Pecking Drilling with Variable Parameters Processing Method as Drilling of CFRP and Ti Stacks.” *J. Manuf. Process.,* Vol. 117, pp. 355-365 (2024).

Iqbal, A., Zhao, G., Zaini, J., Jamil, M., Nauman, M.M., Khan, A.M., Zhao, W., He, N., and Suhaimi, H., “CFRP Drilling under Throttle and Evaporative Cryogenic Cooling and Micro-lubrication.” *Compos. Struct.,* Vol. 267, 113916 (2021).

Khan, S.A., Nazir, A., Mughal, M.P., Saleem, M.Q., Hussain, A., and Ghulam, Z., “Deep Hole Drilling of AISI 1045 via High-speed Steel Twist Drills: Evaluation of Tool Wear and Hole Quality.” *Inter. J. Adv. Manuf. Technol.,* Vol. 93, pp. 1115-1125 (2017).

Kim, D.W., Lee, Y.S., Park, M.S., and Chu, C.N., “Tool Life Improvement by Peck Drilling and Thrust Force Monitoring during Deep-micro-hole Drilling of Steel.” *Inter. J. Mach.Tools Manuf.,* Vol. 49, pp. 246-255 (2009).

Li, S., Wu, Y., Yamamura, K., Nomura, M., and Fujii, T., “Improving the Grindability of Titanium Alloy Ti-6Al-4V with the Assistance of Ultrasonic Vibration and Plasma Electrolytic Oxidation.” *CIRP Ann.,* Vol. 66, No. 1, pp. 345-348 (2017).

Lium F,, Chenm T,, Duanm Z,, Suom Y,, and Zhang, C., “Ultrasonic Assisted Pecking Drilling Process for CFRP/Ti Laminated Materials.” *J. Manuf. Process.,* Vol. 108, pp. 834-851 (2023).

Liu, Y., Zhang, D., Geng, D., Shao, Z., Zhou, Z., Sun, Z., Jiang, Y., and Jiang, X., “Ironing Effect on Surface Integrity and Fatigue Behavior during Ultrasonic Peening Drilling of Ti-6Al-4V.” *Chinese J. Aeronaut.,* Vol. 36, No. 5, pp. 486-498 (2023).

Lu, J., Ni, L., Wang, S., and Mao, X., “Grey-Taguchi Analysis and Experimental Assessment of 1 GPa HSLA Steel Treated by Quenching and Tempering.” *J. Mater. Res. Technol.,* Vol. 29, pp. 3508-3521 (2024).

Makhdum, F., Phadnis, V.A., Roy, A., and Silberschmidt, V.V., "Effect of Ultrasonically-assisted Drilling on Carbon-fibre-reinforced Plastics." *J. Sound Vib.,* Vol. 333, No. 23, pp. 5939-5952 (2014).

Peace, G.S., Taguchi Methods: A Hand-on Approach, Addison-Wesley, Reading, MA (1993).

Pujana, J., Rivero, A., Celaya, A., and López de Lacalle, L.N., "Analysis of Ultrasonic-assisted Drilling of Ti6Al4V." *Inter. J. Mach. Tools Manuf.,* Vol. 49, No. 6, pp. 500-508 (2009).

Rodriguez-Alabanda, O., Romero, P.E., and Guerrero-Vaca, G., "Application of Custom Macro B High Level CNC Programming Language in A Five-axis Milling Machine for Drilling Holes Distributed in Axi-symmetric Working Planes." *Procedia Manuf.*, Vol. 41, pp. 976-983 (2019).

Shard, A., Agarwal, R., Gupta, V., and Garg, M.P., "Influence of Ultrasonic Vibrations during Drilling of Arbon-fiber-reinforced Polyetherimide Composite." *Appl. Acoust.,* Vol. 202, pp. 109-163 (2023).

Taguchi, G., Elsayed, E.A., and Hsaing, T., Quality Engineering in Production Systems, McGraw-Hill (1989).

Tiwari, A.K., and Panda, S.S., "Optimization of Process Parameters in ECDM Machining using Taguchi Based Grey Relation Analysis." *Measurement,* Vol. 216, 112971 (2023).

Wang, C.H., Li, P.N., Li, S.J., Qiu, X.Y., Niu, Q.L., Li, C.P., and Ko, T.J., "Study on the mechanism and performance of longitudinal-torsional ultrasonic vibration assisted drilling CFRP/Ti stack." *J. Manuf. Process.*, Vol. 92, pp. 453-465 (2023).

Wang, M., Yu, H., Xu, J., Chen, G., Dai, B., and Wang, S., "Amplitude Effect on Micro-hole Drilling of 3D Needled Cf/SiC by Ultrasonic Vibration." *Ceram. Inter.,* Vol. 47, No. 24, pp. 34987-35001 (2021).

Yang, H., Ding, W., Chen, Y., Laporte, S., Xu, J., and Fu, Y., "Drilling Force Model for Forced Low Frequency Vibration Assisted Drilling of Ti-6Al-4V Titanium Alloy." *Inter. J. Mach. Tools Manuf.,* Vol. 146, 103438 (2019).

Zhang, X., Lu, Z., Sui, H., and Zhang, D., "Surface Quality and Residual Stress Study of High-speed Ultrasonic Vibration Turning Ti-6Al-4V Alloys." *Procedia CIRP*, Vol. 71, pp. 79-82 (2018).

Zhang, Y., Li, L., Xie, C., Lou, J.C., "The Theoretical Model of Straightness Error in Gun Drilling of Small Diameter and Deep Hole." *Inter. J. Adv. Manuf. Technol.,* Vol. 122, pp. 3447-3465 (2022).

Zhang, Z., Wu, L., Jia, S., and Peng, T., "Multi-objective Parameter Optimization to Support Energy-efficient Peck Deep-hole Drilling Processes with Twist Drills." *Inter. J. Adv. Manuf. Technol.,* Vol. 106, pp. 4913-4932 (2020).

Zhang, Z.J., Zhang, S.H., Zhang, J.C., Jin, X., and Liu, B.B., "A Parametric CNC Programming Method for Rapid Battlefield ManufacturingF." *Adv. Mater. Res.*, Vol. 346, pp. 440-446 (2012).