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Ultrasonic-assisted drilling of nickel-based super alloy in conel 601: An experimental study

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Abstract. In this study, a comparison between ultrasonic-assisted drilling (UAD) and conventional drilling (CD) is presented under different feed rates using thrust force, torque, and hole geometrical errors as output responses. The experiments were done on plates of Inconel 601 (nickel-based superalloy), which is classified as a difficult-to-cut alloy due to its high Nickel content (60%), high hardness (43 HRC), and low thermal conductivity. The experiments were performed using DMG Mori Ultrasonic 20 linear, which is equipped with ultrasonic tool holderoscillating at 20 kHz with 7 μm amplitude. A coated carbide single margin twist drill had been used in the experiments. Full factorial design of experiments approach was employed, and the results had been statistically analyzed to find the most significant factor affecting the process responses. The results showed that the ultrasonic assistance had reduced the thrust force, and torque compared to conventional drilling (CD). Also, a reduction in holecylindricity error was detectedduring UAD, whichimprovesthe hole quality. In case of UAD, twist drills did not suffer from a physical wear, however notch wear was observed in CD drills. Chip morphology was also studied. Short segmented chips were obtained when using UAD which improved chip evacuation and reduced the chance of chip jamming in the drill flutes.

1. Introduction

Since the invention of the aircraft gas turbine, a steady increasingdemand for materials showing higher mechanical properties at elevated temperatures appeared. This requirement drove the motivation to develop high temperature alloys which has resulted in many useful alloys to meet a variety of applications. One family of these alloys is Ni-based superalloys. They exhibit high mechanical strength, ductility, creep strength at high working temperatures, high fatigue strength, and also an excellent resistance to oxidation and corrosion even at elevated operating temperatures[1].

On contrast, from the machining point of view, these superior properties made the cutting of such alloys more complicated and,consequently,they were classified as difficult-to-cut alloys. During machining, a major portion of superalloys strength is preserved due to their high temperature properties. Even though superalloys are not very hard at room temperature (the hardness range being about 25-40 HRC)[2], they create difficulties during machining due to their tendency for work hardening. The work hardening quickly occursand results in high cutting forces, burr formation and notch wear at the cutting edges during machining. Also, the poor thermal conductivity of superalloys generates high concentrated temperature at the tool tip, which decreases the tool life[1, 3].

As a result of the low machinability of superalloys, it was crucial to find new techniques to machine these difficult-to-cut alloys instead of conventional ones. Ultrasonic-assisted drilling (UAD); using high frequency and low amplitude oscillations, is a promising technology in drilling superalloys[4]. In this study, one of these Ni-based superalloys (Inconel 601) was investigated to evaluate the effect of UAD technique on the process performance compared with conventional drilling (CD).

UAD process is similar in concept to the CD in many aspects; it uses conventional twist drill as a cutting tool, which rotates and feeds axially in z-direction, however in UAD ultrasonic oscillations are superimposed in the direction of feed as shown in Figure1. The main challenge in this process is how to build a system to generate the ultrasonic oscillations, work in the resonance mode, and transmit the oscillations to the cutting tool without any harmful effect on machine tool spindle. Three proposed designs were introduced. First one, through the design of a non-rotary ultrasonic tool holder and give the rotational speed to the workpiece[5, 6]. Secondly, design of a rotary tool holder and transmit theelectrical signal from power generator to the piezoelectric ceramics via two different techniques; using slip rings[7-12], or inductive transmission system[13-15]. Last technique is by transmitting oscillations to the workpiece not cutting tool[16-19].

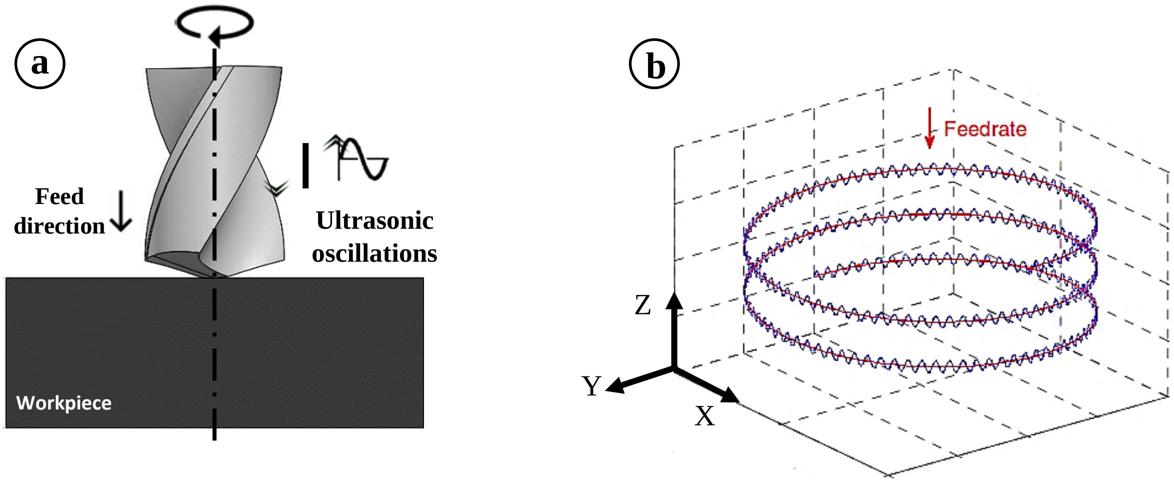

Figure 1. (a) Schematic drawing of ultrasonic-assisted drilling operation (b) the trajectory of any point on the cutting edges of twist drill during UAD.

Ultrasonic assistance (UA) improves hole quality alongall drilling stages from the beginning to the end of hole. In the first stage, chisel edge begins to contact with workpiece, and ultrasonic oscillations help in drill quick penetration; plays as a centering operation, so they reduce tool skidding (displacement) and more location accuracy could be obtained[20]. After that the main cutting edges start to penetrate into the workpiece. Due to UA, chips become more segmented, which facilitate chip evacuation from drill flutes[5, 21]. Chip segmentation helped in cutting forces reduction. Azghandi, et al. [21] concluded that UAD showed a significant decrease in thrust force of around 60% compared to CD when cutting high alloyed steel (X20Cr13). Furthermore, with increasing the oscillation amplitude, the drilling force was slightly decreased. Also, tool wear was significantly reduced when UAD was applied, which increased tool life[6, 21, 22]. UAD improved hole geometrical quality, as it was found that UAD provided better hole circularity, cylindricity and reduced hole surface roughness drastically [23, 24]. At hole exit, UAD playeda crucial role in burrs elimination, because the last layer in workpiece is cut not punched as in case of CD. So, a decrease in burrs height and width was observed[6, 17, 25].

2. Experimental Procedure

In this study, the Inconel 601 (Ni-based superalloy) workpiece material was supplied as plates of 25 mm width, 200 mm long, and 6.45 mm thick. The chemical composition of Inconel 601 as analyzed by WDXRF Spectrometer is provided in Table 1. The hardness measurement value was 43 HRC.

Table 1. Chemical composition of Inconel 601.

C	**Si**	**S**	**Cr**	**Ni**	**Al**	**Ti**	**Co**	**Cu**	**Mo**	**Nb**
0.06	0.20	0.003	**22.80**	**59.20**	1.23	0.38	0.08	0.11	0.39	0.14

All experiments were performed on DMG Mori Ultrasonic 20 linear machining center which is specially designed for ultrasonic-assisted machining operations and equipped with distinctive HSK ultrasonic toolholder. The toolholder contains the piezoelectric crystals as the oscillators and the electric signal is transmitted to the oscillators via wear-free inductive system, which enables the full compatibility to the automatic tool changers as shown in figure 2. The ultrasonic system has 300-Watt power generator with frequency range from 17.5 to 48 kHz. In order to avoid any oscillations from being transferred back to the spindle, the connection point between the transducer and the tool holder is in the nodal plane, where the oscillation is zero. The cutting tool used in this study was a single-margin AlTiN-coated carbide twist drill with a 6-mm diameter, supplied from Kyocera-SGS tools. The drills had 140° point angle and 30° helix angle with a full length of 63 mm. It was recommended to minimize the tool overhang, in order to minimize the radial vibrations which might affect the drilled hole quality. All experiments were performed using water-based emulsion cutting fluid with a concentration of 10%. figure 3 shows the twist drill fixed to the ultrasonic tool holder and the external cutting fluid tubes are targeted to drill tip.

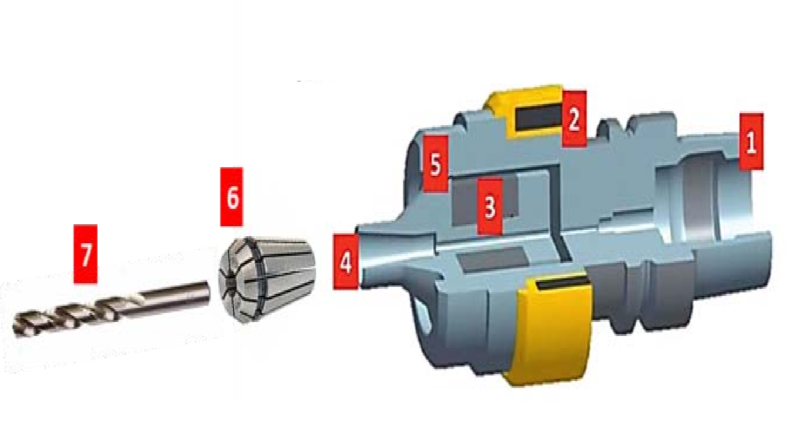

Figure 2. ultrasonic actuator system consisting of (1) HSK interface, (2) inductive signal transmission system, (3) piezoelectric transducer, (4) tool interface, (5) vibration-free mounting flange, (6) ER-11 collet, and (7) twist drill**.**

Figure 3. Drill fixation to the US-toolholder.

The experiments were designed to study the effect of changing feed rates on the responses with the application of ultrasonic oscillations (UAD) at 20 kHz and amplitude of 7 µm and without (CD).The frequency and amplitude of oscillation are fixed in all experiments. The tool manufacturer recommended to use 10 m/min surface cutting speed (rotational speed: 530 rpm) todrill Inconel 601, so it was fixed in all experiments. Feed rate values used in the present investigation were 0.020, 0.035, 0.050 mm/rev. Number of test runs was 6with 2 replications as shown in table 2.

Table 2. Test runs of the design matrix**.**

Drilling Technique	**Feed rates**		
	0.020 mm/rev.	0.035 mm/rev.	0.050 mm/rev.
CD	1	2	3
UAD	4	5	6

Three different responses were recorded to assess the performance of ultrasonic and conventional drilling while changing feed rates. The responses measured were; thrust force, torque, and cylindricity error.For the measurements of thrust force and torque, a Kistler dynamometer type 9272 was used with charge amplifier type 5070A connected to the computer with USB cable as shown in figure4. A special fixture was designed to clamp the workpieces to the dynamometer based on dynamometer manufacturer recommendations to ensure measurements accuracy and precision (figure5). Hole geometrical errors were measured using CNC Coordinate Measuring Machine (Model: Mitutoyo CRYSTA-Apex S 544) with a resolution of 1 µm.

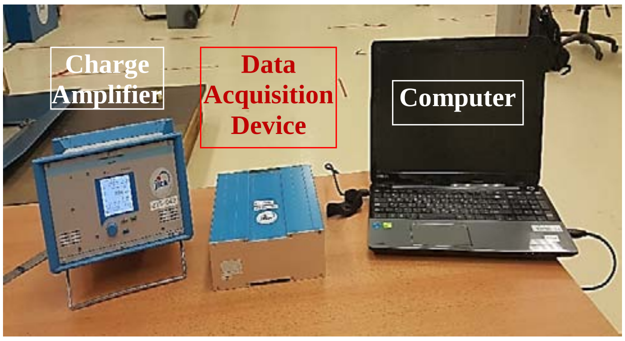

Figure 4. Kistler hardware system used in torque and force measurements

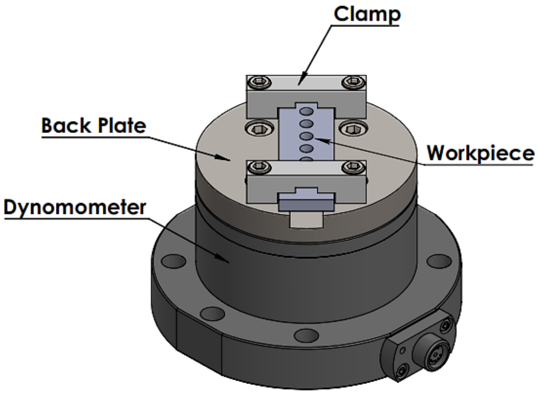

Figure 5. Fixture designed for workpiece clamping and fixed to the dynamometer with 4 bolts.

3. Results and discussion

3.1. Thrust force and torque

Drilling of Inconel 601 was a challenging process, due to its high hardness, and high mechanical properties, which may appear in thrust force and torque plots in figure 6.UAD shows a clear reduction in the values of thrust force and torque for the same cutting conditions. As a result of UAD, an average reduction of 18.5% and 20% in thrust force and torque values were observed respectively.

Figure 6 shows the plots of thrust force and torque at the three selected feed rates. Each plot represents a comparison between CD and UAD values against drilling time. The dotted lines represent the position of twist drill through the drilling operation. The mean values of thrust force and torque had been obtained from the steady cutting zones in these plots, which are located between the two dotted lines (from drilling depth of 0.8 mm to 6.4 mm).All torque plots demonstrated that the torque values of CD are saddling the torque values of UAD, whereas the plots of the thrust force in UAD are located below those of CD. As a result of the superimposed ultrasonic oscillations on the drilling operation in UAD, the thrust force on the first 0.8 mm depth in workpiece is less than in CD through all feed rates. The ultrasonic oscillations work as a hammering process, so they guide the tool during drilling, which reduce the tool skidding (displacement) and, therefore, reduce the thrust force. After the depth of 0.8 mm, the main cutting edges of the drill is totally engaged in the workpiece. Consequently, the effect of ultrasonic impact action begins which leads to more segmented chips than that in CD. Segmented chips are easier to evacuate from the drill flutes which reduce the possibility of chip jamming, and tool breakage. Also, increasing in tool life and improving the hole quality can be realized.

Regarding the torque plots, it is noticed that the amplitude (distance between peak and valley) of UAD plot is larger than that of CD due to the tool separation process as the drill leaves and engages again into the workpiece during the ultrasonic oscillations. At the depth of 6.45 mm, where the chisel edge reaches the bottom surface of workpiece, while the main cutting edges are still in engagement, thrust force and torque begin to decrease to their minimum values.

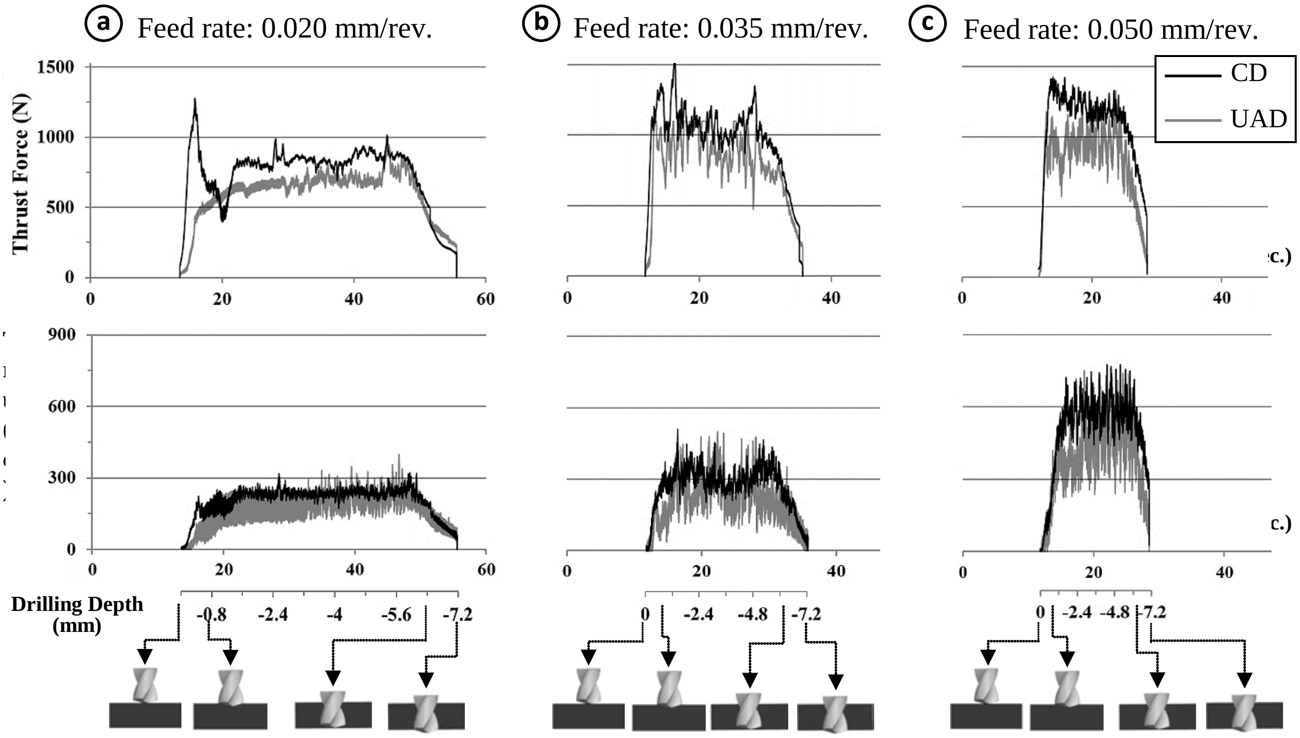

Figure 6. Thrust force and torque plots vs time and drilling depth for different feed rates (a) 0.02 mm/rev. (b) 0.035 mm/rev. (c) 0.05 mm/rev. NB: the dotted lines illustrate the position of twist drill during cutting.

Figure 7 shows that the mean values of thrust force and torque are increased with increasing feed rates for the two techniques CD and UAD. However, the rate of increase of thrust force and torque with increasing the feed rate in UAD is not equivalent to that in CD. Figure 7(b). shows that the mean torque value for feed rate of 0.05 mm/rev. is significantly higher than that at low and medium feed rates.

In most metals and alloys, the last layers of workpiece at hole exit are usually transformed to burrs. However, in case of Inconel 601, the last layers did not form burrs, but were pierced to form a cup as shown in figure 8. This phenomenon occurred during both CD and UAD processes, which can be attributed to the high shear strength of Inconel 601, so the cup was pierced as a result of the thrust force at the end of cut. The indentation lines formed due to ultrasonic oscillations were clearly noticeable on the cup at UAD as shown in figure 8, while the cup from CD had only the usual circular machining marks (lays).

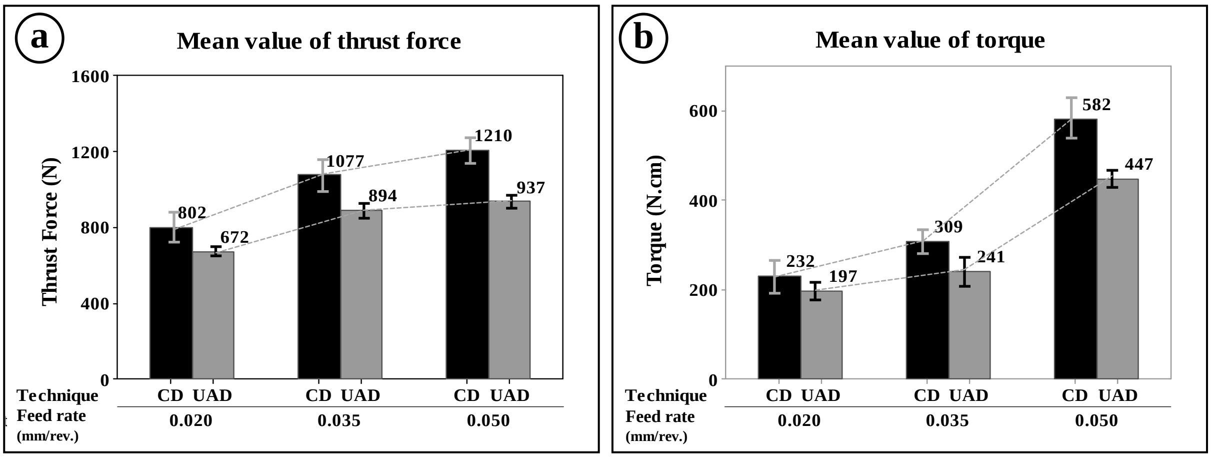

Figure 7. Bar chart of the mean values of (a) thrust force and (b) torque during the drilling of Inconel 601 using conventional drilling (CD) and ultrasonic-assisted drilling (UAD) with different feed rates (N=530 rpm).

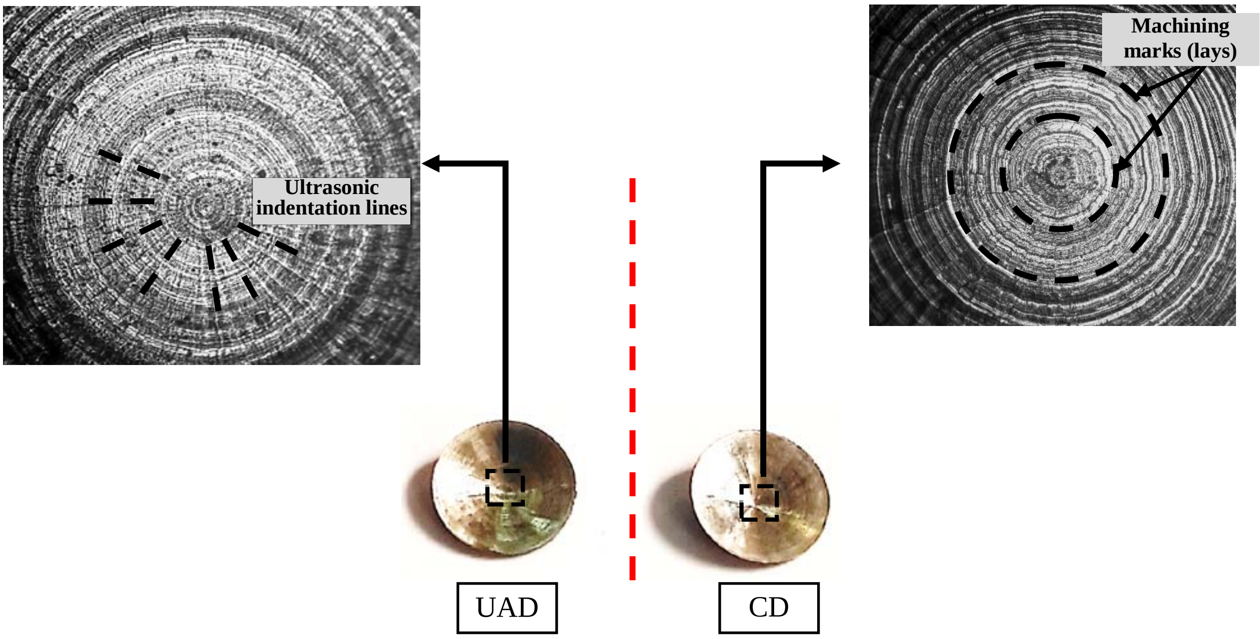

Figure 8. The cup formed due to piercing at the end of cut in UAD and CD.

In order to define the most significant factor affecting the responses, ANOVA approach was used for both thrust force and torque. The analysis of thrust force demonstrated that the two factors; drilling technique (A) and feed rate (B) are significant, but the feed rate change is slightly more effective than drilling technique as shown in figure 9. On the other hand, the effect of feed rate factor is more significant in case of torque response as demonstrated in figure 10(a). Also, in figure 10 (b,c) the main effects plot and the interaction plot are shown respectively. The effect of interaction factor (AB) is minimum. So, in order to reduce thrust force and torque during the drilling of Inconel 601, lower feed rates should be selected.

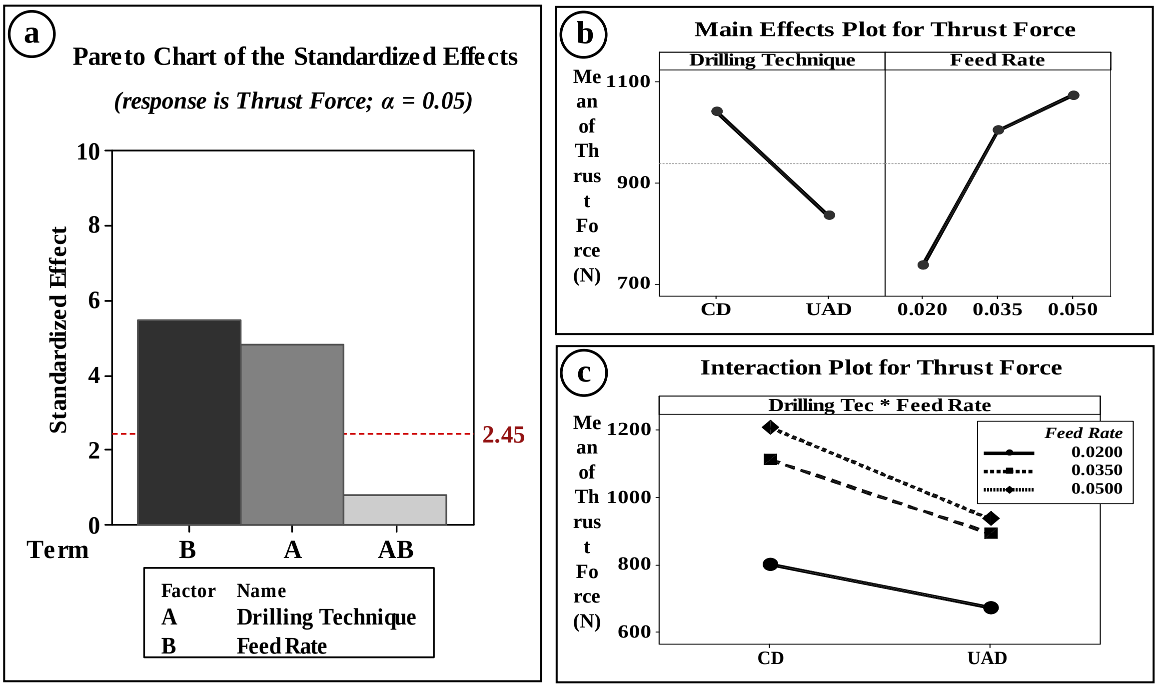

Figure 9. ANOVA results for thrust force (a) pareto chart for the significant factors, (b) main effects plot, (c) Interaction plot.

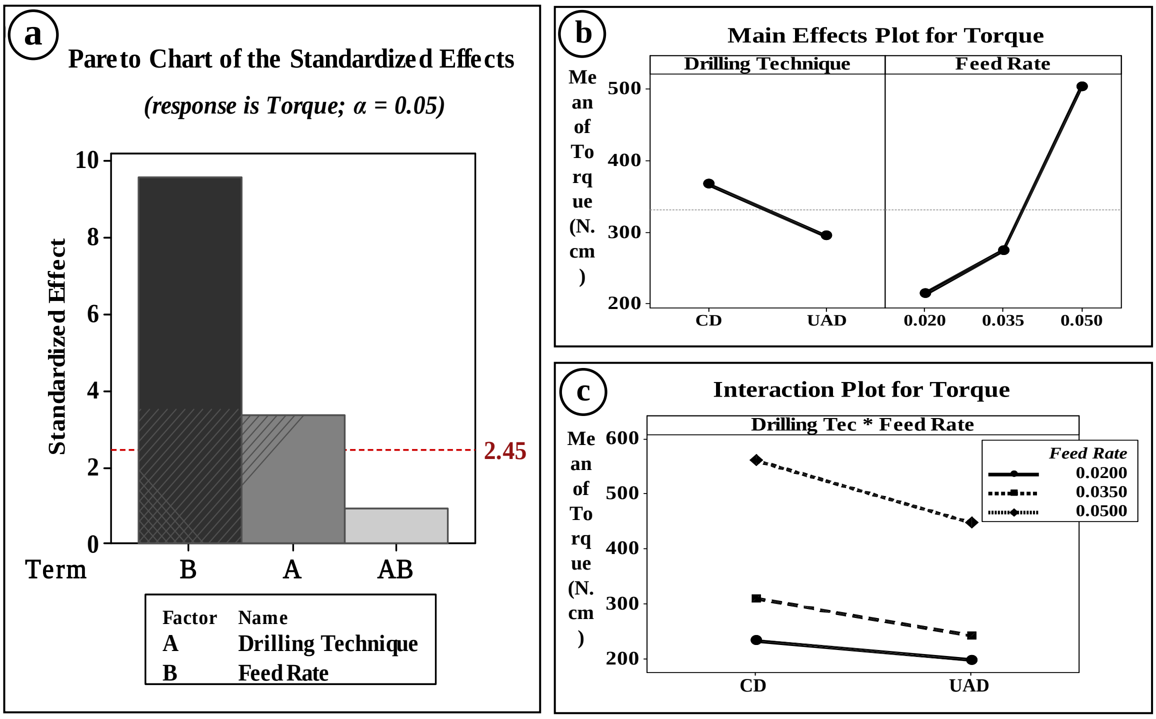

Figure 10.ANOVA results for torque (a) pareto chart for the significant factors, (b) main effects plot, (c) Interaction plot.

3.2. Hole quality

In order to evaluate the hole quality, the cylindricity error of the produced holes was measured using a CNC CMM by probing 40 points randomly through the hole surface. Then, the least square cylinder method had been employed to calculate the cylindricity error. Figure 11 shows the bar chart of mean values of cylindricity error for the test matrix. Using UAD, cylindricity error was reduced significantly than that in CD by 33%. Due to force and torque reduction in UAD process, the drill cutting edges are less affected by the radial displacement (tool skidding). Additionally, the axial ultrasonic oscillation helps in tool alignment through the entire depth of hole, which reduces the cylindricity error and, therefore, improves the hole quality.

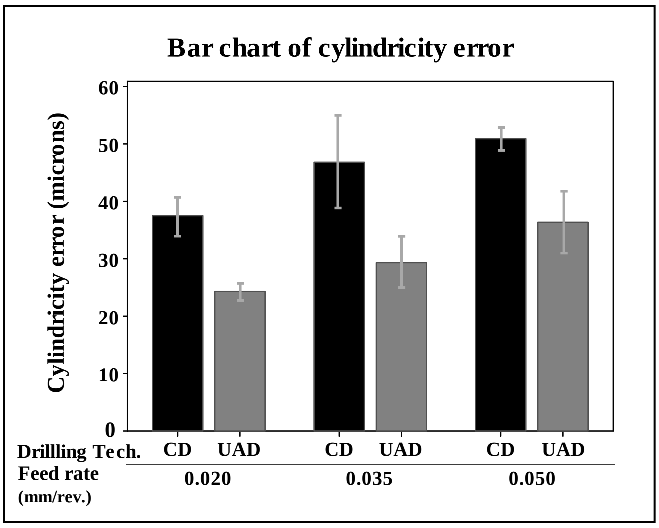

Figure 11. Bar chart of drilled hole cylindricity error at different feed rates using CD and UAD using constant surface cutting speed 10 m/min.

3.3. Tool wear

In order to investigate the tool wear, A MEJI microscope equipped with a digital camera was employed. The experiments were designed to use a new drill every 6 CD experiments and a new one for every 6 UAD experiments. After analysis, the drill used for UAD experiments did not suffer from wear, only scratches in the coating layer (figure 12-a),while no physical wear occurs to the tool.

On the other hand, CD tool suffered from a notch wear as shown in figure 12(b), which lead to BUE adhesion in this location. Tool-workpiece separation process due to the ultrasonic oscillation helped in the dissipation of heat from the cutting zone and the reduction of the pressure (stress) on the cutting edges, which lead to minimize the chance of tool chipping as compared toCD. Furthermore, it helped in the renewal of the cutting fluid with consequent reduction of tool temperature and tool wear.

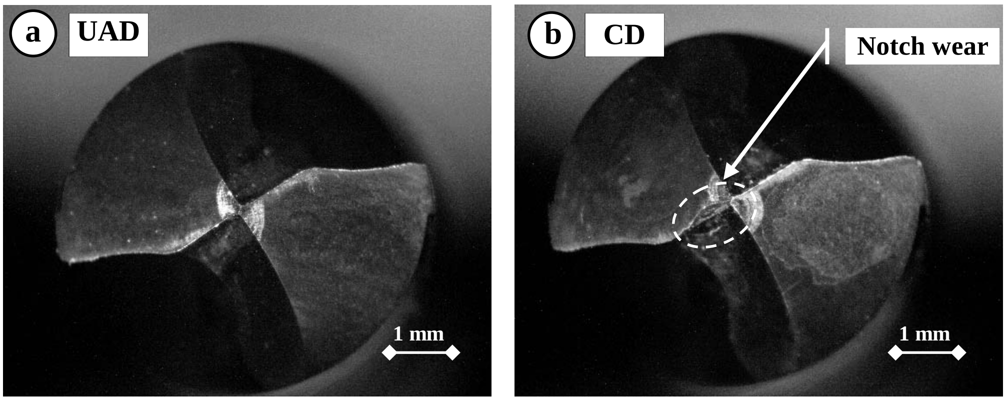

Figure 12. Tools wear after drilling using (a) UAD, (b) CD.

3.4. Chip morphology

As mentioned before, one of the reasons that makes UAD more effective is the chip segmentation. As shown in figure 13(a), segmented chips were obtained while cutting with UAD, however short continuous chips were also noticed in UAD in the beginning of cut due to the material ductility. On contrary, chips obtained in CD were long continuous chips as shown in figure 13(b). Long continuous chips might cause severe chip jamming inside the narrow helical flutes and edge chipping, leading to early tool wear and breakage, poor hole quality and decreased machining productivity.

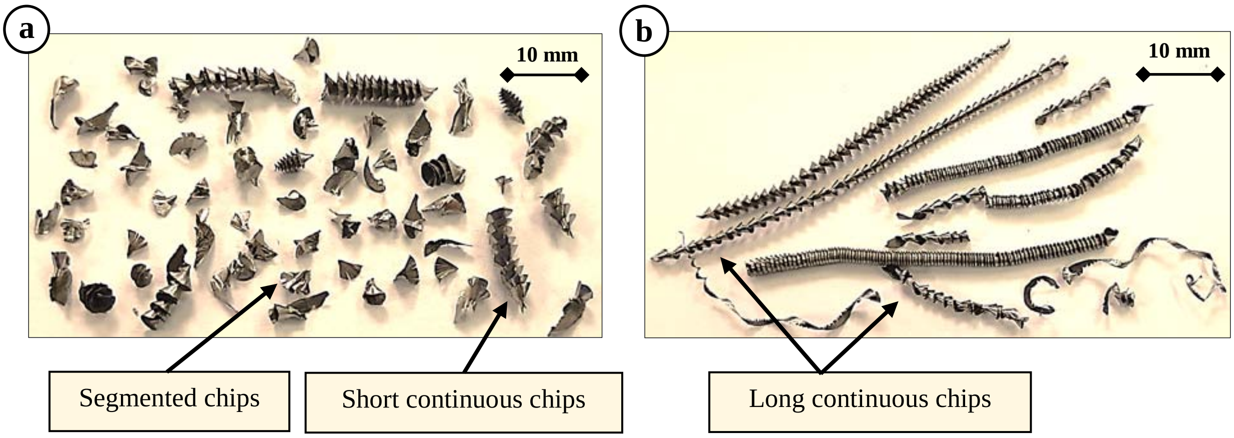

Figure 13. Chips morpholgy during (a) UAD process, (b) CD process.

4. Conclusions

In this study, experimental investigations on drilling of Ni-based superalloy (Inconel 601) were performed using conventional drilling (CD) and ultrasonic-assisted drilling (UAD). A set of experiments was designed using AlTiN-coated carbide drills to explore their effects on thrust force, torque, hole quality, and tool wear. It can be concluded that;

- When UAD was applied, thrust force decreased by 18.5% in average, compared with that in CD.
- At higher feed rates, thrust force increased in UAD and CD, however the rate of increase in thrust force was not steep as in case of CD.
- Torque is also reduced during UAD by 20% in average,compared with that in CD.
- In case of thrust force, ANOVA demonstrated that the two factors; feed rate and drilling techniques were significant and almost have the same effect.
- However, in case of torque, the feed rate factor was more significant than the drilling technique.
- UAD improves drilled hole quality as hole cylindricity error was reduced by 33% than that in CD.
- Notch wear and BUE adhesion was observed in CD, while in UAD the drill wear was minimum.
- Segmented chips were obtained while cutting with UAD, but in CD long continuous chips were observed.
- The indentation lines formed due to ultrasonic oscillations were clearly noticeable on the pierced cup at UAD.

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