Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

International Journal of Machine Tools & Manufacture ▮ (▮▮▮▮) ▮▮▮–▮▮▮

INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION

www.elsevier.com/locate/ijmactool

Ultrasonic-assisted drilling of Inconel 738-LC

B. Azarhoushang, J. Akbari*

School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

Received 15 July 2006; received in revised form 7 October 2006; accepted 16 October 2006

Abstract

Generally in the drilling of modern aviation materials such as nickel and titanium base super alloys, problems frequently occur in terms of burr formation at the cutter exit, tool stress, high heat generation on tool surface as well as low process reliability. A recent and promising method to overcome these technological constraints is the use of ultrasonic assistance, where high-frequency and low-amplitude vibrations are superimposed on the movement of cutting tools. This paper presents the design of an ultrasonically vibrated tool holder and the experimental investigation of ultrasonically assisted drilling of Inconel 738-LC. The circularity, cylindricity, surface roughness and hole oversize of the ultrasonically and conventionally drilled workpieces were measured and compared. The obtained results show that the application of ultrasonic vibration can improve the hole quality considerably. Improvements of up to 60% have been achieved.

Keywords: Drilling; Rotary ultrasonic machining; Ultrasonic-assisted drilling; Nickel-based super alloys; Hole quality

1. Introduction

A range of new alloys and composite materials are being developed every day for various engineering applications. Many of these new materials are difficult to drill with the existent conventional drilling (CD) technology. CD of modern nickel- and titanium-based super alloys used in aerospace applications and in gas turbine blades causes high tool temperatures and subsequently rapid wear of cutting edges due to their high strength and abrasivity even at relatively low cutting speeds. A growing demand for machining these intractable materials requires new advanced drilling technology. A recent and promising technique to overcome these technological constraints is known as ultrasonic-assisted drilling (UAD). The principle of this technique is adding high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 μm) in the feed direction to the tool or workpiece. This cutting process is distinct from ultrasonic drilling. Ultrasonic drilling, also known as rotary ultrasonic machining, is a specific class of ultrasonic machining. In ultrasonic machining, metal removal is effected with the help of abrasive grains suspended in a slurry, which are made to strike repeatedly upon the workpiece surface by a tool oscillating ultrasonically. Ultrasonic drilling is an ultrasonic machining process with a rotating cylindrical tool. The rotation of the tool enhances the abrasive process and causes higher accuracy when generating cylindrical shape elements. Ultrasonic drilling is only applicable to brittle materials. On the other hand, UAD is a hybrid process of CD and ultrasonic oscillation. It is applicable to both ductile and brittle materials. Different researchers have reported significant improvements in thrust force, burr size, tool wear and noise reduction and surface finish. Chang and Bone [1] have shown that burr size reduction in drilling aluminium is possible with UAD. Neugebauer and Stoll [2] have experimentally demonstrated that in UAD of aluminium alloys, force and moment reductions of 30–50% are possible and the reduced load of the tool's cutting edge enabled an up to 20-fold increase in tool life over conventional cutting. Zhang et al. [3] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Onikura et al. [4,5] utilized a piezoactuator to generate 40 kHz of ultrasonic vibration in

*Corresponding author. Tel.: +98 21 616 5535; fax: +98 21 600 0021.
E-mail address: akbari@sharif.edu (J. Akbari).

0890-6955/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2006.10.007

the drilling spindle. They found that the use of ultrasonic vibration reduces the friction between chip and rake face, resulting in chips which are thinner and can therefore lead to the reduction of cutting forces. Jin and Murakawa [6] found that the chipping of the cutting tool can effectively be prevented by applying ultrasonic vibration and tool life can be prolonged accordingly. Takeyama and Kato [7] found that the mean thrust force in drilling can be greatly reduced under ultrasonic vibrations. Drilling chips are thinner and can be removed more easily from the drilled hole. Burr formation at the entrance and the exit sides is greatly reduced with the low cutting forces. Thus, the overall drilling quality is improved with the employment of UAD.

Using ultrasonic vibrations in machining processes causes considerable advantages for machining intractable materials. It has been shown that the use of ultrasonic vibration in turning procedures improves the surface quality significantly and reduces the width of the hardened surface layer, a result of the extensive deformation and high-temperature processes during the turning procedures. It also reduces the average cutting forces up to several times in the process [8,9].

In this investigation, a UAD system has been designed, fabricated and tested. Improvements of cylindricity, circularity, hole oversize, drill skidding and inner surface roughness of the drilled hole due to superimposing of ultrasonic vibration in the drilling of Inconel 738-LC have been obtained. The effect of vibration amplitude, spindle speed, feed rate on cylindricity, circularity and surface roughness has been investigated. The use of two different coated drills for tool wear reduction has also been studied.

2. Design and fabrication of UAD system

In order to study UAD, an actuated tool holder has been designed and built. Fig. 1a illustrates schematically the experimental set-up. The tool holder consists of a piezoelectric transducer, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency (21 kHz) electrical impulses. These high-frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (21 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the horn and transmitted to the drill attached to the horn. The resultant vibration of the drill fixed in the tool holder reaches 10 μm (i.e. 20 μm peak to peak) at a frequency of about 21 kHz. Vibration is applied to the drill in the feed direction of the workpiece. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The workpiece is clamped in the chuck of a universal lathe and rotates at a constant speed. The experimental set-up used to study UAD is shown in Fig. 1b.

The design for the UAD acoustic head is based on the following considerations:

1. Effective vibration of the drill is achieved when it is used as a wave guide (another tune length) for amplification of vibration amplitude. So modal analysis was used to

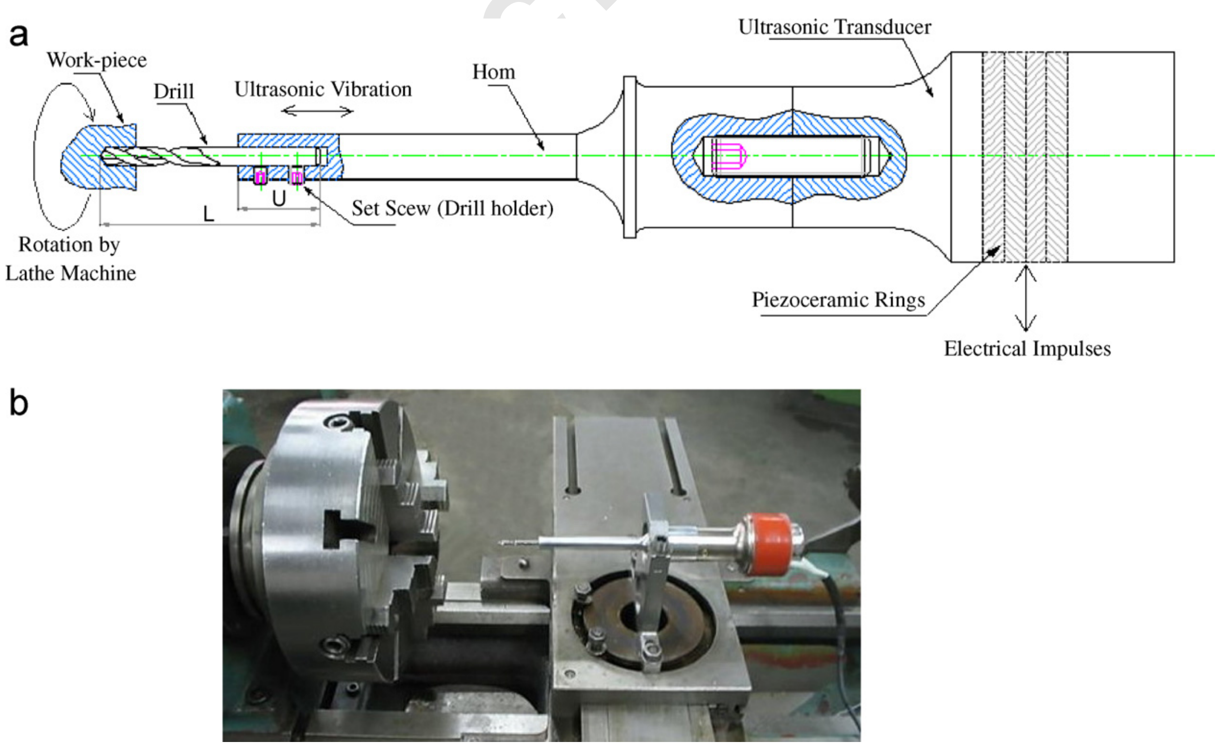

Fig. 1. (a) Scheme of the experimental set-up. (b) Experimental set-up for ultrasonic assisted drilling.

Please cite this article as: B. Azarhoushang, J. Akbari, Ultrasonic-assisted drilling of Inconel 738-LC, International Journal of Machine Tools & Manufacture (2006), doi:10.1016/j.ijmachtools.2006.10.007

find the optimum total length of the drill (L) and the optimum length of the drill part which is inside the horn (U) (see Fig. 1a), so that the acoustic head may reach a resonance frequency of about 21 kHz (the desired vibration condition).

2. The whole structure must possess enough stiffness to withstand the dynamic loads during the drilling operation. The acoustic head parts should have high fatigue resistance and low acoustic losses (meaning that they should not absorb too much energy from the vibrations). Each part of the acoustic head is made of aluminium 7075-T6 with high strength, high fatigue resistance and very good acoustic properties to provide enough stiffness and low acoustic losses. The fixture which clamps the acoustic head is made of steel.

3. Experiments

The experimental equipment consists of the following:

- Universal lathe machine (Tabriz-TN40A): to perform drilling experiments.
- Column drilling machine (Tabriz-MR2): to perform drilling experiments.
- Generator (Mastersonic MMM generator-MSG.1200.IX): to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency range of the generator is 19.020 to 46.728 kHz and the frequency step is 1 Hz. The power of the generator is 1200 W and the maximum output current is 3 A.
- Laser displacement metre (Keyence LC-2430): to measure the amplitude of vibration. The sampling rate of this sensor is 50 kHz. The resolution is 0.01 mm and the laser beam spot is 12 mm.
- CNC three axial CMM machine (Cincinnati-DISK LK G80): to measure the hole cylindricity, hole circularity and hole oversize.
- Hand held surface roughness tester (Time group, TR200): to measure the surface roughness of the drilled holes.
- Toolmakers microscope (Olympus-STM): to observe the burrs at the cutter exit, which possesses a maximum magnification of 200 times with a resolution of 0.5 mm.
- Drill: Diameter of 5 mm, TiAlN-coated carbide drills (Dormer-R522) and TiN-coated carbide drills (Dormer-R550).
- Workpiece material: Inconel 738-LC ($45 \times 35 \times 8\,mm^3$).
- UAD performed without coolant (i.e. dry cutting).

Inconel 738-LC is a high-grade heat-resistant Ni-based super alloy widely used in the gas turbine blades and aerospace industry. The excellent material toughness results in difficulty in chip breaking during the process. In addition, precipitate hardening of γ'' secondary phase (Ni_3Nb) together with work-hardening during machining makes the cutting condition even worse. All these difficulties lead to serious tool wear and less material removal rate (MRR). This material is very abrasive and causes tool blunting and high cutting temperatures when machined conventionally.

4. Experimental results and discussion

In this experiment, the tests were carried out for both UAD and CD with the same instrument. However, during the CD the ultrasonic generator was switched off. All CDs were unsuccessful and the drills broke at the cutter exit. It is thought that the reason for this phenomenon was because the drills were caught in the burrs formed during drilling at the cutter exit, resulting in the breakage of the drills. Fig. 2 shows photographs of the burrs produced at the cutter exit during the drilling tests. In order to be certain that the problems which arise in drilling Inconel 738-LC with CD is not related to the unit stiffness, several drilling experiments was performed with a column drilling machine which is much more stable. Again, at the cutter exit, the drill was caught in the burrs resulting in the levitation of both workpiece and fixture. In this stage, the fixture was not fixed to the machine table (see Fig. 2e). Once the fixture was fixed to the machine table the drill broke at the cutter exit.

The effect of vibration amplitude, spindle speed and feed rate on the circularity, cylindricity and surface roughness were studied. The drills used were standard TiAlN coated carbide drills. Each drill was used to drill four specimens for each test.

Figs. 3–5 show that the relationships between vibration amplitude and circularity, cylindricity and surface roughness are not linear. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation.

Owing to the breakage of the drill in CD at the cutter exit it was not possible to measure the cylindricity of the hole. However, entrance circularity and inner surface roughness of the holes were measured.

Results show significant improvement for UAD compared to CD in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip. The axial oscillation causes the cutting edges to move towards the feeding direction, so that the oscillating and feeding motions are in one direction and therefore add up and both velocities are overlapping. The maximum oscillating velocities (up to 80 m/min) are generated at the amplitude of 10 μm and a frequency value of 21 kHz.

The larger the vibration amplitude, the smaller the axial feed of the tool per each vibration. Therefore, the cut becomes discontinuous and ultrasonic impact action (UIA) occurs, thus causing the material to begin to rollover more

Please cite this article as: B. Azarhoushang, J. Akbari, Ultrasonic-assisted drilling of Inconel 738-LC, International Journal of Machine Tools & Manufacture (2006), doi:10.1016/j.ijmachtools.2006.10.007

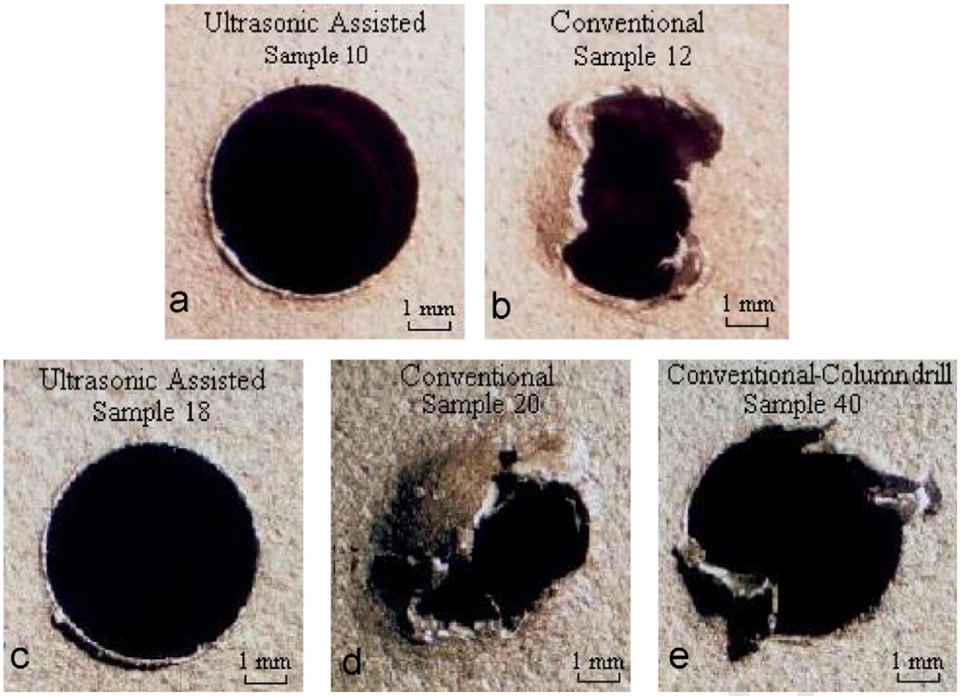

Fig. 2. Burr types samples at drill exit: (a) 250 RPM, 21 kHz, $f = 0.8$ mm/s, $A = 10$ µm. (b) 250 RPM, $f = 0.8$ mm/s. (c) 350 RPM, 21 kHz, $f = 0.5$ mm/s, $A = 10$ µm. (d,e) 350 RPM, $f = 0.5$ mm/s (A = amplitude, f = feed rate).

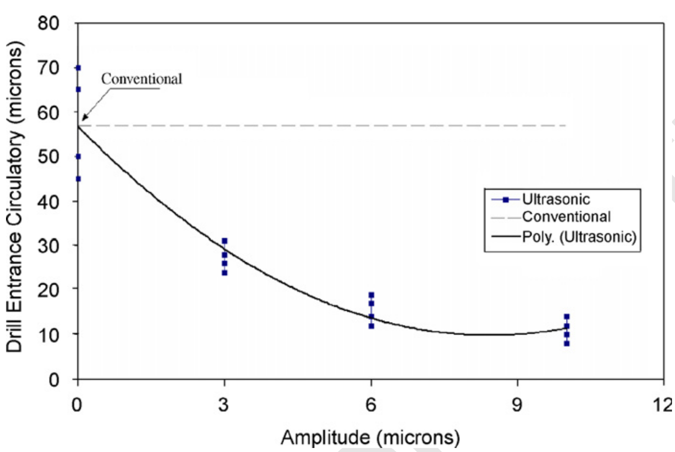

Fig. 3. Drill entrance circularity vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

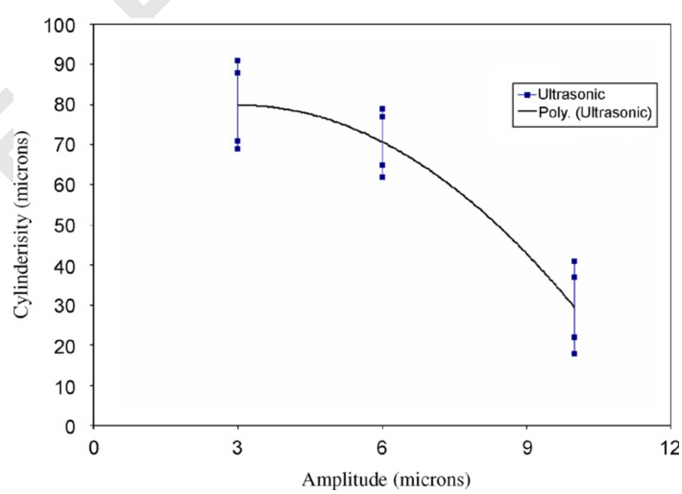

Fig. 4. Drilled hole cylindricity vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

easily. This causes the thrust force to decrease, resulting in less plastic deformation and smaller chips and burrs.

Figs. 6–8 compare the circularity, cylindricity and surface roughness produced by UA drilling with CD under different spindle speeds.

In contrast to CD where the cutting speed is zero at the tool centre and cutting conditions are accordingly unsuitable; in UAD because of the oscillation speed, the working speed in the drill centre is different from zero and therefore the material is rolled over more easily and quickly into the main cutting edges by the chisel edge.

In general cases, increasing spindle speed reduces the uncut chip thickness and cutting forces, resulting in thinner and smaller chips which are easily removed from the hole and lead to better hole quality. However, the preventing parameter is temperature. Increasing spindle speed causes high cutting temperatures and tool blunting and requires high system stability. It is shown that increasing the spindle speed up to 350 rpm has no significant effect on hole quality, but when it reaches 500 rpm, cutting temperatures drastically increase and therefore the hole quality decreases dramatically.

The comparison has been made between the circularity, cylindricity and surface roughness produced by UAD with CD under different feed rates in Figs. 9–11. The relationships are again non-linear.

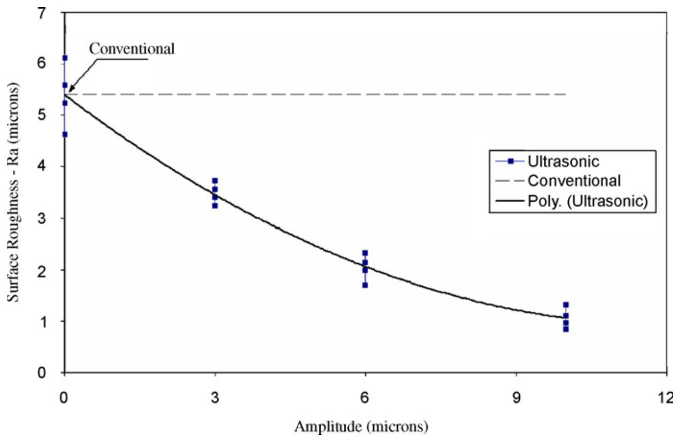

Fig. 5. Drilled hole surface roughness (Ra) vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

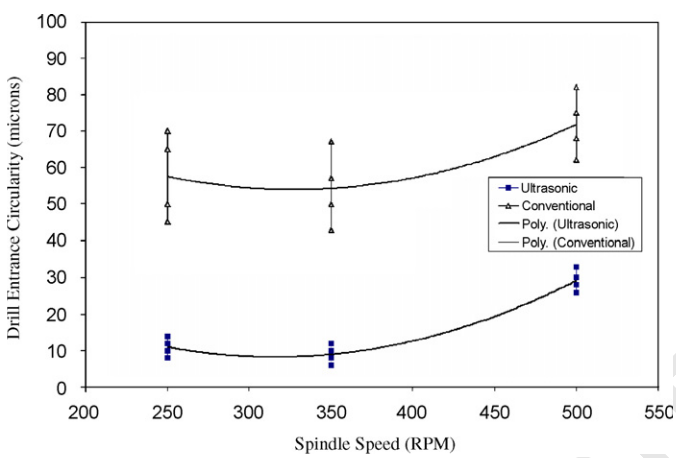

Fig. 6. Drill entrance circularity vs. spindle speed (5 mm diameter drill, $A = 10$ µm, $f = 0.5$ mm/s, 21 kHz).

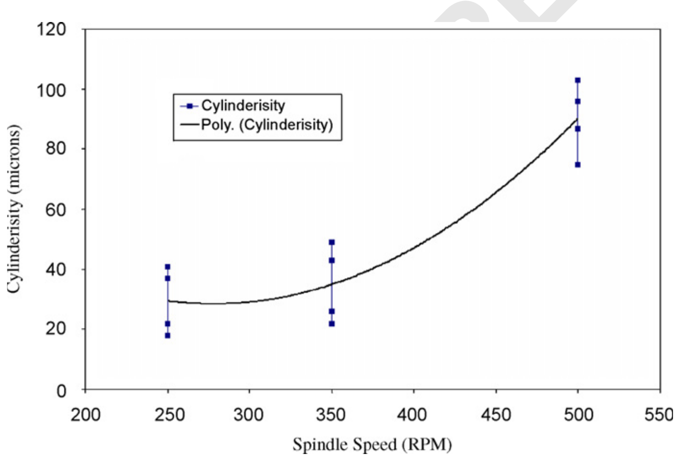

Fig. 7. Drilled hole cylindricity vs. spindle speed (5 mm diameter drill, $A = 10$ µm, $f = 0.5$ mm/s, 21 kHz).

Results illustrate a substantial improvement for UAD compared to CD in different feed rates. As it is shown, hole quality degrades rapidly at higher feed rates. This is because at higher feed rates the uncut chip thickness and cutting forces increase and the chip segmentation effect of the UIA is reduced. Another important factor is the system stability; when feed rate reaches 1 mm/s, the cutting forces

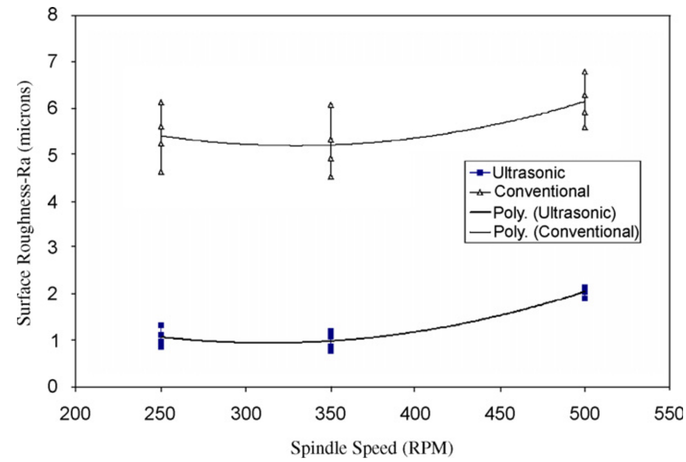

Fig. 8. Drilled hole surface roughness (Ra) vs. spindle speed (5 mm diameter drill, $A = 10$ µm, $f = 0.5$ mm/s, 21 kHz).

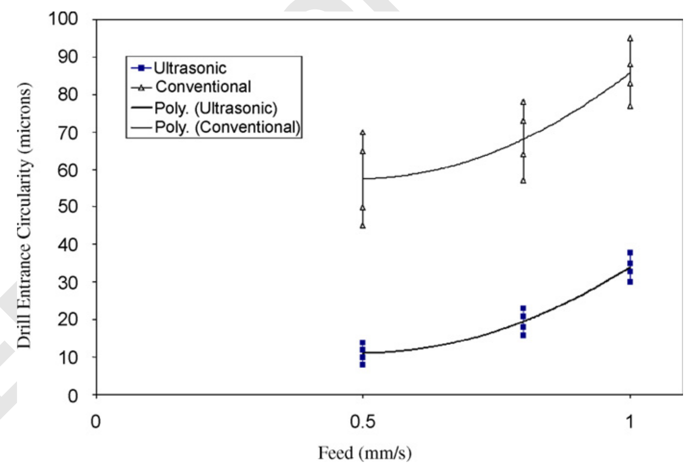

Fig. 9. Drill entrance circularity vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10$ µm, 21 kHz).

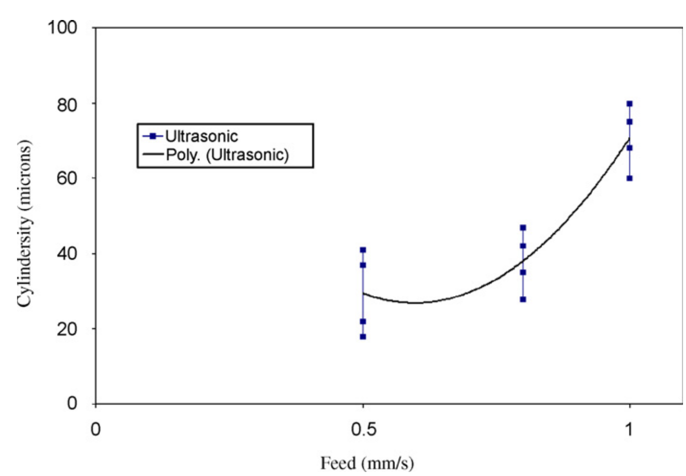

Fig. 10. Drilled hole cylindricity vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10$ µm, 21 kHz).

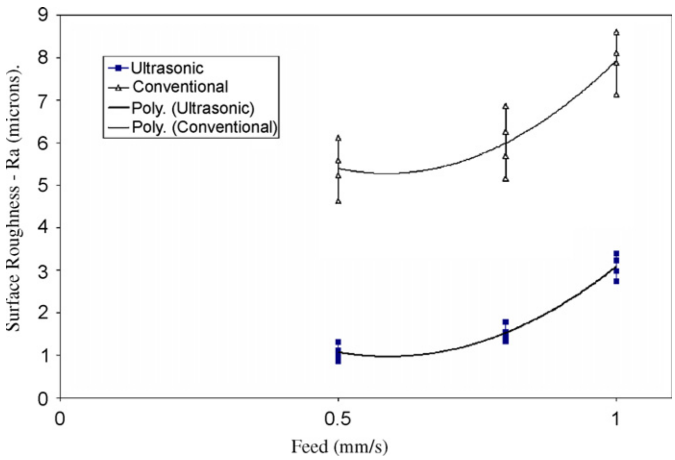

Fig. 11. Drilled hole surface roughness (Ra) vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10\,\mu m$, 21 kHz).

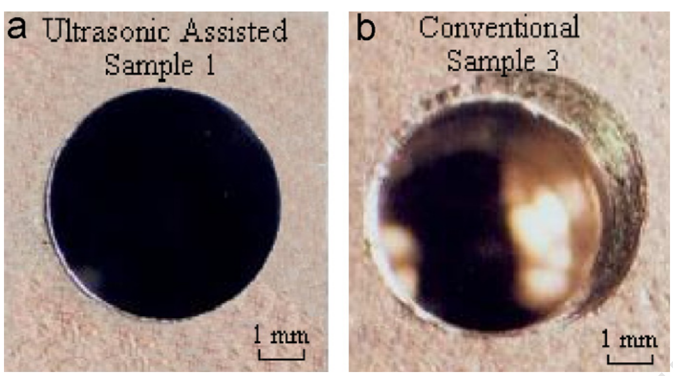

Fig. 12. Drill skidding samples at drill entrance: (a) 250 RPM, 21 kHz, $f = 0.5$ mm/s, $A = 10\,\mu m$. (b) 250 RPM, $f = 0.5$ mm/s.

rise substantially and system stability reduces considerably. These conditions reduce the hole quality significantly.

It should be noted that the scatter in the measured surface roughness and circularity values obtained through UAD is much less compared to CD. It means that using UAD increases the repeatability of the process.

It was also found that using UAD leads to significant improvements on the hole oversize and drill skidding. Fig. 12 shows that in the same conditions, between CD and UAD, the UAD technique almost eliminates drill skidding and helps the drill to penetrate downward quickly. In fact when using UAD there is no need for a centre hole (in the UAD experiments centre holes were not made prior to drilling). Because ultrasonic vibrations are axial, they improve hole alignment by decreasing the drill tip displacement on the surface of the workpiece. Hole oversize reduces significantly with the use of UAD. Average hole oversize in CD was about H11 (5.075 mm) but in UAD (in the same condition) it was reduced to H9 (5.030 mm). This improvement is related to the effects of ultrasonic vibration on reducing cutting forces and drill tip displacement/skidding.

The chip morphology was also examined. CD produced long, continuous chips. On the other hand, the chips produced by UAD are discontinuous with small serrations and the cross-sections of these chips are influenced by superimposing ultrasonic oscillations with CD (see Fig. 13).

In the next stage of investigation, two different types of coated carbide drills, solid carbide TiAlN coated drill (Dormer-R522) and solid carbide TiN-coated drill (Dormer-R550) were used in several drilling experiments without the use of a coolant. TiAlN-coated drill was used to drill four holes at 250 RPM, $f = 0.5$ mm/s, $F = 21$ kHz, $A = 10\,\mu m$. Based on the result from the previous stage, it is believed that UAD performs better under these conditions. These conditions are not essentially the optimal ones.

It was found that TiN-coated carbide drill can not withstand the high cutting temperatures which are produced in drilling Inconel 738-LC. Fig. 14a shows TiN-coated drills after drilling two holes.

The results show that UAD can effectively reduce the chipping of the cutting tool and therefore tool life can be prolonged accordingly. This was expected, because the ultrasonic action reduces cutting and friction forces and also cutting temperatures. Fig. 14b shows TiAlN-coated drills after drilling four holes. It was observed that during CD the drill always broke at the cutter exit, therefore in order to prevent the breakage of the drill the experiments (both CD and UAD) were only resumed up to the point where 2 mm was left to the other side of the workpiece (2 mm to the cutter exit). Therefore, as the thickness of the workpieces were 8 mm, the drilling hole length was approximately 6 mm.

As is shown in Fig. 14b, the tool wear for CD is more significant. Abraded-off coated layer, chipping and breakage of cutting edge can be observed as the tool wear in CD. After drilling the third hole BUE started to form at the drill edges during CD. This was due to the fact that after drilling the first two holes, abrasion of the coated layer took place causing an increase in friction force which plays a key role at the beginning stage of tool wear. The tool wear in UAD is less than CD and the coated layer is only slightly abraded and chipping with micro-cracks only occurred near the chisel edge.

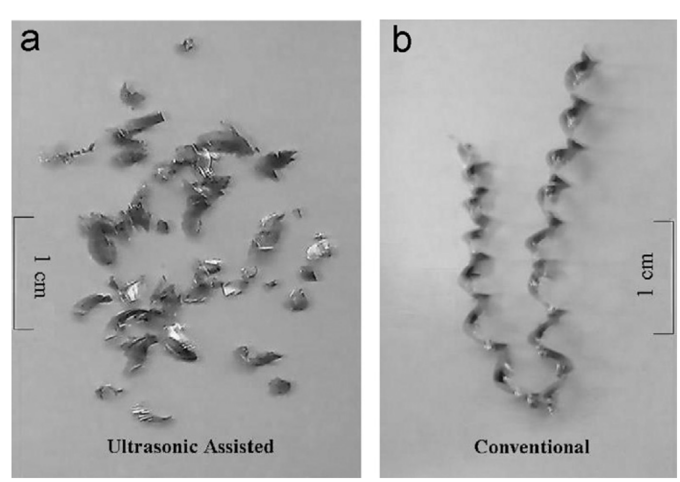

Fig. 13. Chip morphology: 250 RPM, 21 kHz, $f = 0.5$ mm/s (for UAD, $A = 10\,\mu m$).

Please cite this article as: B. Azarhoushang, J. Akbari, Ultrasonic-assisted drilling of Inconel 738-LC, International Journal of Machine Tools & Manufacture (2006), doi:10.1016/j.ijmachtools.2006.10.007

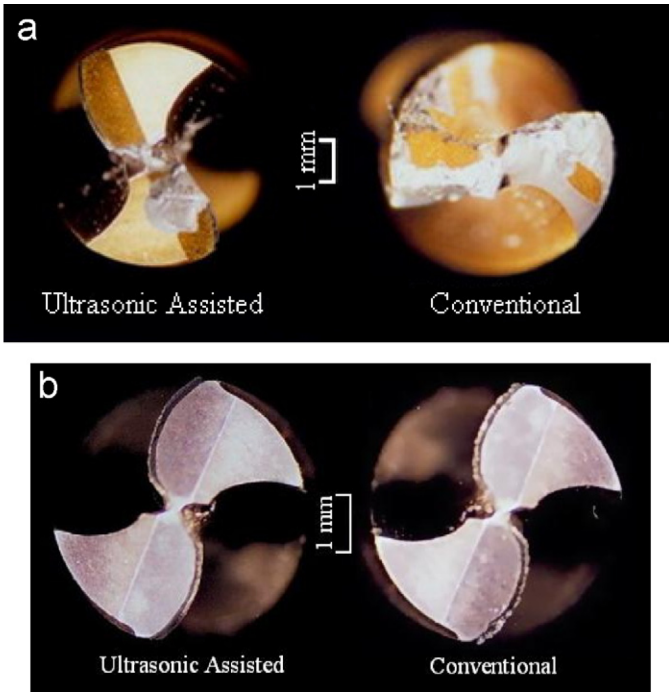

Fig. 14. (a) Worn TiN-coated drills from tests performed at 250 RPM, 21 kHz, $f = 0.5$ mm/s. (b) Worn TiAlN-coated drills from tests performed at 250 RPM, 21 kHz, $f = 0.5$ mm/s (for UAD, $A = 10\,\mu$m).

In addition to the above-mentioned explanations, another reason for hole quality improvements in UAD is that the oscillations are divided into two steps; in the first step, oscillation is positive and is added up with the feed motion, therefore the effective rake angle is significantly enlarged in comparison to the rake angle of the drill, where as the effective clearance angle hardly eliminates compared to the drill's clearance angle. In the second step, there is a reverse in ratios as a result of reversing direction. The technological parameters such as the oscillating amplitude, the oscillating frequency and the tool speed, effect the curve of the amount of angular changes.

The angular variation explained above essentially contributes to the UAD effects. Because of the large effective rake angles that are produced in the first oscillation step, the chip easily slips along the cutting edge. In the second oscillation step, the effective rake angle is significantly reduced. As a result of constant angular variation, the adhering of the chip to the drill edges is avoided, particularly to the tool face. In this way, the friction on the tool is considerably reduced. This effect also reduces the cutting moment in the process and the emerging chip can be removed from the hole easily. Therefore, it applies less pressure on the chip root, which may lead to a smaller plastic flow zone and cause less burning on the drill.

5. Conclusion

Experimental studies of UAD and CD demonstrate considerable advantages of the former technology for machining Inconel 738-LC. Comparative experiments of the hole quality demonstrated up to 60% improvement in average surface roughness and circularity for the workpieces machined with superimposed ultrasonic vibration. All CDs were unsuccessful and the drills broke at the cutter exit. It is thought that the reason for this phenomenon was because the drills were caught in the burrs formed during drilling at the cutter exit, resulting in the breakage of the drills. It was also found that using UAD leads to significant improvements on the hole oversize and drill skidding. These improvements are subjected to the change of the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in discontinuous and finer chips and reducing the thrust force acting on the workpiece. This way friction on the tool is decreased. This effect reduces the cutting moment in the process and the emerging chip can be removed from the hole easily. Therefore, it applies less pressure on the chip root, which may lead to a smaller plastic flow zone and smaller burrs and cause less burning on the drill and the tool life can be prolonged accordingly.

Acknowledgements

The authors would like to thank the Kavosh Azmoon company, for supplying required drills for this investigation and the Beshel Motor Industries, for allowing us to use their CNC three axial CMM machine.

References

[1] S.S.F. Chang, G.M. Bone, Burr size reduction in drilling by ultrasonic assistance, International Journal of Robotics Computer-Integrated Manufacturing (21) (2004) 442–450.
[2] R. Neugebauer, A. Stoll, Ultrasonic application in drilling, Journal of Materials Processing Technology (149) (2004) 633–639.
[3] L.B. Zhang, L.J. Wang, X.Y. Liu, H.W. Zhao, X. Wang, H.Y. Luo, Mechanical model for predicting thrust and torque in vibration drilling fibre-reinforced composite materials, International Journal of Machine Tools & Manufacture (41) (2001) 641–657.
[4] H. Onikura, O. Ohnishi, J.H. Feng, T. Kanda, T. Morita, U. Bopp, Effects of ultrasonic vibration on machining accuracy in microdrilling, International Journal of JSPE 30 (3) (1996) 210–216.
[5] H. Onikura, O. Ohnishi, Drilling mechanisms in ultrasonic-vibration assisted micro drilling, Journal of JSPE 64 (11) (1998) 1633–1637 (in Japanese).
[6] M. Jin, M. Murakawa, Development of a practical ultrasonic vibration cutting tool system, Journal of Materials and Processing Technology (113) (2001) 342–347.
[7] H. Takeyama, S. Kato, Burrless drilling by means of ultrasonic vibration, Annals of CIRP 40 (1) (1991) 83–86.
[8] V.I. Babitsky, A.N. Kalashnikov, A. Meadowsa, A.A.H.P. Wijesundara, Ultrasonically assisted turning of aviation materials, Journal of Materials Processing Technology (132) (2003) 157–167.
[9] V.I. Babitsky, A.V. Mitrofanov, V.V. Silberschmidt, Ultrasonically assisted turning of aviation materials: simulations and experimental study, Journal of Ultrasonics (42) (2004) 81–86.