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Ultrasonically Assisted Turning: Effects on Surface Roughness

Naseer Ahmed

Department of Mechanical Engineering, College of Engineering,
Taibah University, Madinah Al Munawwarah, Saudi Arabia

Abstract: Ultrasonically assisted turning (UAT) is a special type of machining where frequency in the range of 20kHz and amplitude of 20μm is utilized in addition to the usual cutting forces. The introduction of this additional force has proven its benefits in terms of reduction of cutting forces and improvement of surface finish. The improvement has been beneficial in processing hard-to-cut alloys, composites and ceramics. The paper presents an experimental study performed to study the effect of UAT on the surface roughness of Inconel 718. For comparative study, samples of surface roughness from both Conventional Turning (CT) and UAT are examined.

Key words: Ultrasonically Assisted Turning · Surface Roughness · Inconel 718

INTRODUCTION

Surface analysis studies are critical to process control in many fields of research and industry. Every surface has some form of texture which is generated by the combination of different effects: material's microstructure, the action of cutting tool on the material (tool shape, speed, feed and cutting fluid) and the instability in the cutting tool (e.g. chatter). Surface texture generally consists of irregularities with regular or irregular spacing which tend to form a pattern or texture on the surface. A texture can demonstrate Roughness (Primary texture) and/or Waviness (Secondary texture) (Figure 1). Primary texture consists of the irregularities in the surface texture that results from the inherent action of the production system. These are deemed to include traverse feed marks and the irregularities within them. Secondary texture consists of the component of surface texture upon which roughness is superimposed. Waviness may result from such factors as machine or work deflections, vibrations, chatter and heat treatment.

Ultrasonically assisted turning (UAT) has brought significant benefits to machining of hard-to-cut alloys. In UAT, high-frequency vibration (frequency $f\_ \approx$ 20 kHz, amplitude $a \approx$ 20 μm) is superimposed on the movement of a cutting tool. Compared to CT, this technique results in a multifold decrease in cutting forces and a considerable improvement in surface finish [1-5].

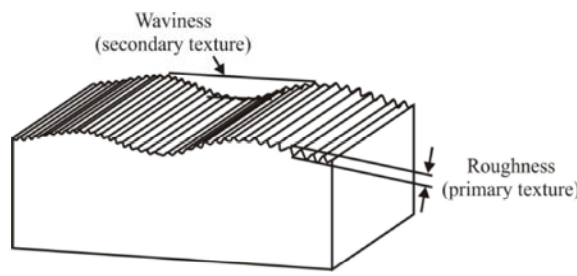

Fig. 1: Roughness and waviness

Babikov in his book [6] summarized some of the research results up to time of its publication about the application of ultrasonic technology to machining of hard and brittle materials. It was shown that ultrasonic processing not only resulted in a providing ease in cutting hard materials but also resulted in finished surface of high quality. Later Frederick [7] also reported that the beneficial effects, which can be obtained by ultrasonic vibration during machining, included: lower residual stresses in hard materials and better surface finish. Experiments were conducted on different materials, e.g. carbon steel C1010 and C1045 and aluminium (2024-T6) in

Corresponding Author: Naseer Ahmed, Department of Mechanical Engineering, College of Engineering, Taibah University, Madinah Al Munawwarah Saudi Arabia.
Mob: +966542173051, Tel: +966-4-8460008 ext 8206.

[8]. The results obtained showed an increase in material removal rates, reduction of the tool load, improvement of surface finish, reduction of subsurface deformation, elimination of the tool built-up edge and extension of the tool life.Ultrasonic assisted cutting was applied to the machining of glass-fibre reinforced plastic in [9]. Chip formation, cutting forces and surface quality were evaluated. It was concluded that by applying ultrasonic machining, average cutting forces and roughness of machined surface are dramatically reduced and also bur and surface damage were improved. Ultraprecision ductile cutting of glass was studied in [10] by applying ultrasonic vibration to a single-crystal diamond tool in the cutting direction. One of the conclusions was that surface finish of soda-lime glass was also improved.An active error compensation scheme incorporated into the ultrasonic cutting technique was proposed in [11] for precise machining and a piezoelectric actuator integrated into a cutting tool was developed. Cutting experiments showed that the integrated cutting tool was effective in terms of improved roundness and roughness of the machined surface.The influence of cutting conditions on the surface microstructure of ultra-thin wall parts in ultrasonic-vibration cutting was studied in [12]. Results were drawn by comparing ultrasonic cutting with common cutting using a cemented carbide tool and a polycrystalline diamond (PCD) tool. The test results showed that surface characterization was influenced clearly by rigidity of the acoustic system and the machine tool. Surface roughness in ultrasonic cutting was better than that in conventional cutting. In [13] experiments were conducted with the workpiece of fused silica of diameter 15 mm and a crystal diamond tool with rake angle 0° and clearance angle 11°. Vibration with frequency 40 kHz and amplitude 3 μm was applied in the cutting direction. From the results of those experiments it was concluded decreasing the cutting speed of the workpiece and/or increasing the vibration frequency resulted in better surface quality. Turning of some modern aviation materials was conducted with ultrasonic vibration applied in the feed direction using an autoresonant control system [14]. Results from experiments showed that the surface roughness was improved by 25-40% for ultrasound vibration compared to conventional cutting.

Description: In order to quantify the surface improvement brought about by UAT, surface analysis studies were performed using two different techniques: the Zygo® interferometry and Talysurf® technique.

Talysurf® is a stylus type surface texture measuring instrument in which the stylus is traversed across the surface and the Pick-ups converts its vertical movement into an electrical signal, which is amplified and used to operate a recorder. The R_a value is derived from the filtered signal and is displayed on either a pointer or digital type meter (Figure 2). The pick-up used in Talysurf® 4 is a variable inductance, position sensitive one that gives a signal proportional to the displacement, even when the stylus is stationary. The output is independent of the speed at which the stylus is displaced and is related only to the position of the stylus within the permissible range of vertical movement. The advantage of this type of pick-up is that it enables a true recording of waviness and forms to be obtained.

Zygo® interferometry characterizes and quantifies surface roughness, step heights, critical dimensions and other topographical features with excellent precision and accuracy. All measurements are non-destructive, fast and require no sample preparation. It provides graphical images and high-resolution numerical analysis to accurately characterize the surface structure of test parts. The Zygo® interferometry instrument NewView™ 5000 series was used for surface analysis. The NewView™ uses interferometric objectives. The objective creates interference by dividing the light into two paths; directing one to an internal reference surface and the other to the test surface. Surface irregularities in the test part causes the reference and the test wave fronts to travel different distances; when recombined they are out of phase and form an interference pattern [15].

Sample Preparation: An Inconel 718 round bar of length 200 mm and diameter 45 mm was held in the chuck of a lathe machine. The eccentricity of the sample was checked with a dial gauge. After setting the eccentricity properly, a uniform cut using CT was performed over the workpiece for a length of 40 mm. The surface resulting from the CT cut was then turned initially with UAT and then CT for a length of 10 mm each. Figure 3 presents the sample showing the two areas turned with UAT and CT.

Surface Analysis Using Talysurf® 4: Samples obtained by both CT and UAT were analyzed for surface roughness analysis using the Talysurf® (Figure 4). Results of surface texture analysis for CT are presented in Figure 5. The average roughness R_a for CT comes out to be 1.9143 μm. Figure 6 presents the surface texture analysis for UAT. R_a for UAT is 0.5052 μm. The results

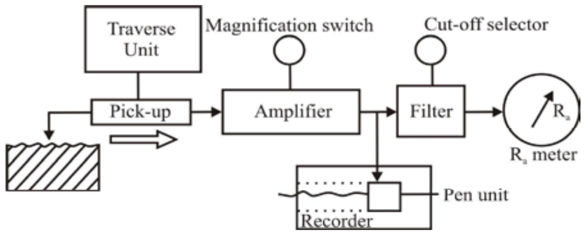

Fig. 2: Diagram showing main constituents of stylus-type surface texture measuring instrument

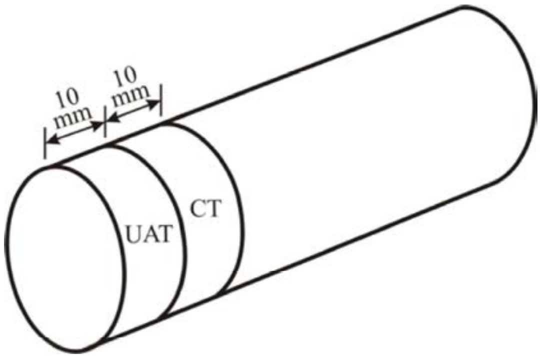

Fig. 3: Sample for surface roughness analysis (depth of cut, d = 0.2 mm, feed rate, s = 0.1 mm/rev, frequency, $f \approx 20$ kHz, amplitude, $a \approx 15$ µm, cutting speed, v = 376 mm/sec)

Fig. 4: Experimental setup for surface roughness analysis using Talysurf 4

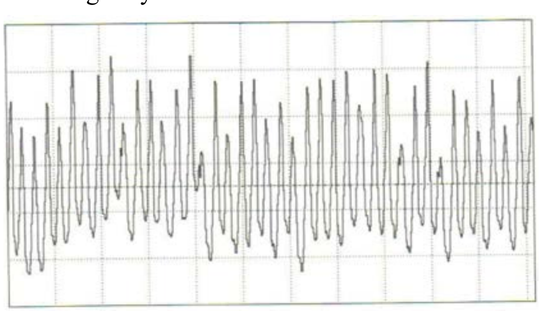

Fig. 5: Surface analysis for CT samples (Vertical scale = 2.00µm/div, Horizontal scale = 0.5 mm/div)

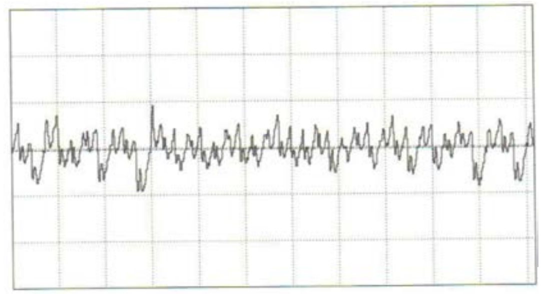

Fig. 6: Surface analysis for UAT samples (Vertical scale = 2.00µm/div, Horizontal scale = 0.5 mm/div)

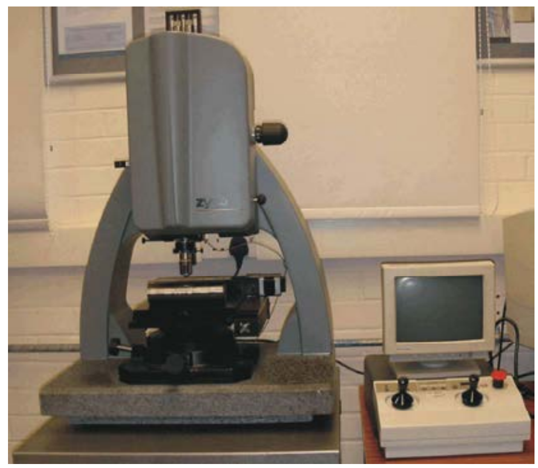

Fig. 7: Experimental setup for surface roughness analysis using Zygo interferometry

prove the importance of vibration-assisted turning in surface roughness as it improved the average roughness by 73%.

Surface Analysis Using Zygo® Interferometry: Surface roughness analysis was also performed using the Zygo® interferometry equipment. Figure 7 shows the actual setup of Zygo® interferometry. Samples were mounted using special magnets onto the test bed. Once properly fitted, the area for analysis was moved just beneath the lens using the X-Y lever (X-Y lever controls the horizontal motion of the test bed). After the proper spot was tracked, the image was fine focused using the Z lever (Z lever controls the vertical motion of the vertical column that houses the lens and other optical instruments).

Surface scan was first obtained for the surface section of the sample machined using CT. Figure 8 presents the intensity map of the surface obtained from the direct observation of the surface via the camera built inside the Zygo® vertical column.

Fig. 8: Intensity plot of CT surface

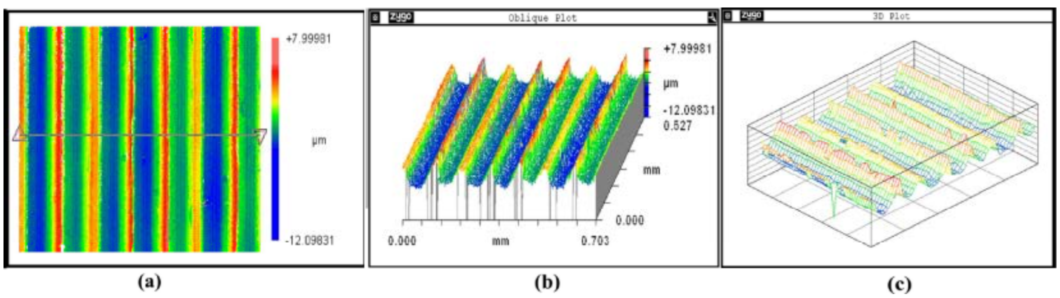

Fig. 9: Zygo results for CT: (a) standard plot; (b) oblique plot; (c) 3D plot

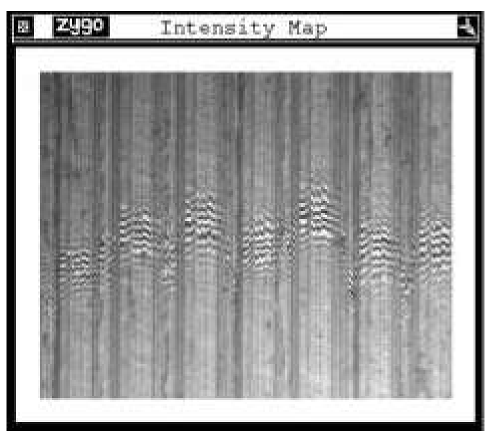

Fig. 10: Intensity plot of UAT surface

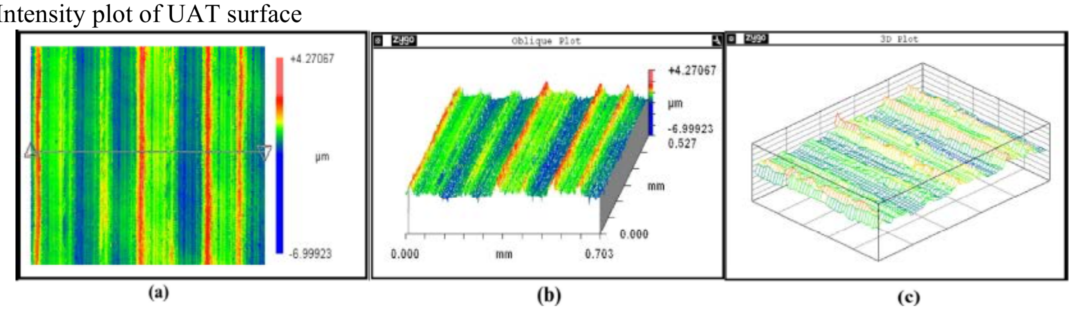

Fig. 11: Zygo results for UAT: (a) standard plot; (b) oblique plot; (c) 3D plot

Table 1: Results of analysis for CT and UAT

Parameters	CT	UAT	%age Difference
PV (µm)	20.098	11.270	44%
rms(µm)	2.081	0.659	68.3%
R_a (µm)	1.719	0.505	70.6%
Size X (mm)	0.70	0.70	-
Size Y (mm)	0.53	0.53	-

Figure 9 presents the generated intensity plots of the CT surface. The height is differentiated using different colour coding: blue represents the lower value while red represents the highest value. The surface irregularities can be clearly seen from the figure. The same plot is reproduced using different methods to ease understanding the various characteristics of the surface. An oblique plot (Figure 9b) provides a better view for understanding the surface features.

Figure 10 presents the intensity plot for the surface of workpiece machined using UAT. Figure 11 presents the regeneration of the intensity plot in term of the colour-coded one. The results obtained from the Zygo® interferometry proved the better surface results in case of UAT as compared to CT. Table 1 presents the comparison of different surface profilometry results for the two surfaces. R_a value in case of CT is 1.719 µm as compared to 0.505 µm in case of UAT. The slight difference between the results of two procedures can be justified by the fact that the observation area in case of Zygo® is very small (0.70 mm   0.53 mm) and it is quite certain that a different area was observed by Zygo® as compared to the one observed by Talysurf® surface profilometry.

CONCLUSION

The paper presented the results of a comparative study between the surface roughness of workpiece machined using techniques such as conventional turning and ultrasonically assisted turning. The surface roughness was recorded using two different analyzers; the contact type and the non-contact type. The results from both,Zygo® interferometry and Talysurf® surface profilometry, are in good agreement. The surface machined using UAT showed an average 72% improvement in surface roughness as compared to the one machined using CT which are in good agreement with the results demonstrated in [8] and [10].

Nomenclature

PV = Peak to Valley, μm

rms = Root mean Square, μm

Ra = Average Roughness, *N*

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