Study of ultrasonically assisted turning of stainless steel and brass alloys

S M A Mahdy1,2,3, M A Gouda1 and V V Silberschmidt2

1Mechanical Engineering Dept., Faculty of Engineering, The British University in Egypt (BUE), El-Shorouk city, Cairo 11837, Egypt
2Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

Email: sameh.mahdy@bue.edu.eg

Abstract. Ultrasonically assisted turning (UAT) is a hybrid machining technique employing high-frequency small-amplitude vibration superimposed on the tool movement during turning. It is superior to conventional turning (CT) with regard to cutting forces, surface quality and machining accuracy. The aim of this study is to investigate the effect of different machining parameters on stainless steel and brass alloys, during both UAT and CT, and evaluate improvements of cutting forces, surface roughness, surface integrity, and machining accuracy. An experimental setup for UAT at Loughborough University was used to accomplish this investigation. This setup used a Picoscope data acquisition add-on with Kistler three-component dynamometer, Seco DNMG cutting inserts were utilized, a surface tester from Taylor Hobson was used to evaluate surface roughness, Alicona Infinite Focus microscope was used to evaluate surface roughness and surface integrity, while Metris CMM with Renishaw probe was employed to evaluate machining accuracy. Cylindrical workpieces of steel and brass alloys were turned under CT and UAT conditions; cutting forces, surface roughness, and machining accuracy produced with both techniques where compared. Significant improvements were noticed in the ultrasonically assisted machining when compared to the CT for both alloys.

1 Introduction
The ultrasonic vibration cutting method is an efficient cutting technique for difficult-to-machine materials [1]. The ultrasonic vibration cutting method is a more effective cutting process than conventional cutting in terms of cutting force, cutting instability, tool blunting, tool wear, chip generation, surface finish and so on, to machine difficult-to-cut materials such as Ni- and Ti-based super alloys, hardened steels, optical glasses, ceramics, tungsten carbides, etc. [1-4]. Ultrasonic Assisted Turning (UAT) is a process of turning a work piece with the help of high-frequency low-amplitude vibrations. This process makes use of the classical lathe machine to superimpose this high-frequency vibration on the tool while cutting. The vibration direction in relation to the tool movements has a great effect on the surface produced [1]. This direction could be either in lateral feed direction or in the longitudinal feed direction [5]. The first moves the tool intermittently in a hammer-wise movement in relation to the work piece’s rotating surface; this movement results in an instantaneous increase in the radial force component. The second direction is linked to the tool movement in a

3 To whom any correspondence should be addressed
direction parallel to the work piece’s rotating axis; this movement results in an instantaneous increase in the axial force component each time the vibratory movement brings tool closer.

The effect of this is the multi-fold decrease of cutting forces as well as improvements of the surface integrity of the produced surface [6, 7]. Also the effect incorporates the enhancements of machining accuracy with the decrease in the cutting force [8]. Introduction of vibration promotes stability of the cutting process; this is achieved thanks to intermittent cutting contact interaction between the tool and the work piece [9]. UAT is investigated nowadays because of its unquestionable benefits when machining hard-to-machine alloys as well as tough materials, with the ability to reach mirror-like surface finish [10]. Also UAT proves to be superior to other processes when machining brittle materials such as glass and ceramics; it machines the surface to the required specifications without the need to costly post-processing operations usually associated with these materials. Aside from the obvious advantages, other effects can include the hardening of the machined surface due to the continuous hammering effect of the tool [11]. Different materials have been studied under UAT to try to evaluate the optimum machining conditions as well as to increase our knowledge in that new area [12]. These materials include super alloys as well as aviation materials, both being perfect candidates for such study because of their hard machinability under conditions of the classical conventional cutting (CT) [13]. Some of the most renowned brittle materials are glass and ceramics. Ultrasonically assisted machining process i.e. UAM, has been utilized in many of the basic metal cutting processes in an effort to improve the process. Ultrasonic Assisted Drilling (UAD) is used to minimize the cutting forces as well as improve the surface produced [2]. Ultrasonic Assisted Milling (UAM) is used with the high speed multi-point cutters to enhance both material removal as well as quality of surface [4]. Ultrasonic Assisted Turning (UAT) can be utilized with either single-direction vibration or two-direction vibration. In single-direction vibration the system vibrates in only one direction and the transducer system is fairly straight forward, while in the case of two-direction vibration (ultrasonic elliptical vibration cutting) the system is much harder to design [14], [12], and [15]. The aim of this paper is to study experimentally the effect of changing different machining parameters on machining stainless steel (SS) and brass under conditions of both CT and UAT.

2 Experimental technique
Experimental work was carried out at Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University, where a Harrison M300 lathe was retrofitted with an ultrasonic vibration attachment to allow for both conventional cutting and ultrasonic assisted turning on the same machine delivering a vibration of a frequency of 20 kHz and an amplitude of 8 µm. This ultrasonic attachment is composed of a band of piezoelectric rings, a horn and a dynamometer; the system is attached to a high-frequency pulse generator as well as a data acquisition system for auto resonance feedback along with force measurements. As shown in figure 1 a cylindrical SS work piece was turned using CT and UAT; both tangential and radial forces where measured (using the dynamometer and the data acquisition with a PC). Surface roughness measurements were taken as shown in figures 2-3, while measuring roundness is presented in figure 4. An experimental plan was designed as follows for both material under investigation.

Figure 1. Experimental setup with SS workpiece mounted, ultrasonic vibration attachment, and cutting tool positioned for cutting: (a) whole setup, (b) cutting-tool view.
2.1 Stainless steel alloy material
In tests the austenitic standard stainless steel grade SAE 304 (BS 304S16 / DIN 1.4301) (ISO designation X2CrNi18-9) was used; this steel has the following composition: [C:0.06/Mn:0.9/Si:1/P:0.05/S:0.02/Cr:18/Ni:8] and properties: tensile strength: 515 MPa, yield strength (0.2%): 205 MPa, density: 8000 kg/m³, elastic modulus: 193 GPa. It was machined using the following machining parameters: cutting speed (v): 25, 30, 35, 40, and 45 m/min; depth of cut (a): 0.1, 0.2, 0.3, 0.4, and 0.5 mm; feed rate (f): 0.03, 0.05, 0.1, 0.16, and 0.2 mm/rev.

2.2 Brass alloy material
It is an alpha/beta brass alloys, which contains copper and zinc (ISO designation: CuZn37Pb2) (BS BZ131 / UNS C35300). This alloy has the following composition: [Cu:62/Pb:2] and the following mechanical properties: tensile strength: 420 MPa, yield strength: 200 MPa, density: 8500 kg/m³, elastic modulus: 105 GPa. It was machined using the following machining parameters: cutting speed (v): 25, 35, 45, and 55 m/min; depth of cut (a): 0.1, 0.2, 0.3, 0.4, and 0.5 mm; feed rate (f): 0.1, 0.16, and 0.2 mm/rev.

2.3 Cutting tool
The cutting insert utilized during experiments is the industrial sintered carbide coated insert from SECO: DNMG 150608 MF1 CP500. This insert is suitable for intermittent metal cutting operations of high-speed steels. Insert as in figure 5 was mounted on a compatible tool holder at the end of the horn whose function was to concentrate the ultrasonic vibration movement at the tool-work piece interface.
3. Results and discussions

3.1. Cutting of stainless steel alloy material

3.1.1. Cutting forces measurement

In general, the cutting forces (tangential $F_t$ and radial $F_r$) increased with the increasing cutting speed ($v$), depth of cut ($a$), or feed rate ($f$) for both cases of CT and UAT as shown in figures 6-8. Apparently, under different cutting conditions the cutting forces in UAT are lower than those in CT. At cutting speed $v = 35$ m/min, as example, the cutting forces $F_t$ and $F_r$ decreased from 162.2 N and 124.3 N in CT to 72.2 N and 71.0 N in UAT, i.e. by 56.2% and 42.9%, respectively. At depth of cut $a = 0.3$ mm, these cutting forces decreased from 177.3 N and 105.9 N in CT to 65.2 N and 42.7 N in UAT (by 63.2% and 59.6%, respectively). At feed rate $f = 0.2$ mm/rev, they decreased from 194.6 N and 149.2 N to 126.0 N and 133.2 N (by 35.2% and 10.7%).

This decrease in cutting forces in case of UAT if compared to the CT is due to the lowering of friction levels between tool and workpiece due to the intermittent nature of tool-chip contact under UAT as stated in [9]. Another reason for that decrease might be attributed to the absorption of ultrasonic vibration energy produces an acoustic softening effect on the material as stated by Skelton et al. [17]. Also the decrease in cutting forces is expected to yield a better surface in case of UAT than in case of CT, as the system stability is enhanced by adding the superimposed vibrations, not limited to the surface improvements only but also to the improvement of the machining accuracy which is the ability of machine to produce required shape with close out of roundness values due to the decrease of the force. Another expected result from vibration action imposed on acoustic softened surface with lowered cutting forces on a much stable system is the close surface roughness values as well as surface integrity due to surface healing with each tool-workpiece hammering action.

Figure 6. Effect of cutting speed ($v$) on tangential cutting force ($F_t$) (a) and radial cutting force ($F_r$) (b) for turning of SS under CT and UAT ($f = 0.2$ mm/rev, $a = 0.3$ mm)
Figure 7. Effect of depth of cut (a) on tangential cutting force ($F_t$) (a) and radial cutting force ($F_r$) (b) for turning of SS under CT and UAT ($v = 35$ m/min, $f = 0.1$ mm/rev)

Figure 8. Effect of feed rate ($f$) on tangential cutting force ($F_t$) (a) and radial cutting force ($F_r$) (b) for turning of SS under CT and UAT ($v = 45$ m/min, $a = 0.3$ mm)

As shown in figures 9-11 the average roughness ($R_a$) and ($S_a$) in case of UAT is lower than that obtained in case of CT; it means that the vibration-assistance turning causes improved surface quality. At cutting speed $v = 30$ m/min, the surface roughness $R_a$ and $S_a$ decreased from $0.1301$ µm and $0.9860$ µm in CT to $0.1185$ µm and $0.9140$ µm in UAT, (by 8.9% and 7.3%, respectively). At depth of cut $a = 0.4$ mm, these parameters decreased from $0.6020$ µm and $0.5360$ µm in CT to $0.3330$ µm and $0.4010$ µm in UAT, which means that the $R_a$ decreased by 44.6% while $S_a$ decreased by 25.1%. At feed rate $f = 0.1$ mm/rev, $R_a$ and $S_a$ decreased from $0.1700$ µm and $0.8890$ µm in CT to $0.1570$ µm and $0.7910$ µm in UAT (by 7.6% and 11%).

Figure 9. Effect of cutting speed ($v$) on average roughness ($R_a$) (a) and average roughness ($S_a$) (b) for turning of SS under CT and UAT ($f = 0.2$ mm/rev, $a = 0.3$ mm)
Figure 10. Effect of depth of cut ($a$) on the average roughness ($R_a$) (a) and the average roughness ($S_a$) (b) for turning of SS work piece under CT and UAT ($v = 35$ m/min, $f = 0.1$ mm/rev)

Figure 11. Effect of feed rate ($f$) on average roughness ($R_a$) (a) and average roughness ($S_a$) (b) for turning of SS under CT and UAT ($v = 45$ m/min, $a = 0.3$ mm)

Machining accuracy measurements

As for the machining accuracy, it was obtained by the out of roundness measurements on the CMM machine. As shown in figures 12-14, the out of roundness ($R_o$) in case of UAT is lower than that obtained in case of CT. It means that the use of UAT results in improved system stability as forces decrease, affecting in their turn the accuracy of the produced surface. From figure 12 at a cutting speed $v = 35$ m/min as example, the out of roundness ($R_o$) decreased from 0.0230 µm in CT to 0.0134 µm in UAT, which means a decrease by 41.7%. At depth of cut $a = 0.4$ mm (figure 13), $R_o$ decreased from 0.0227 µm in CT to 0.0068 µm in UAT, decreased i.e. by 70%. At feed rate $f = 0.16$ mm/rev (figure 14), the out of roundness decreased from 0.0197 µm to 0.0138 µm (by 29.9%).

Figure 12. Effect of cutting speed ($v$) on out of roundness ($R_o$) for turning SS under CT and UAT ($f = 0.2$ mm/rev, $a = 0.3$ mm)

Figure 13. Effect of depth of cut ($a$) on out of roundness ($R_o$) for turning SS under CT and UAT ($v = 35$ m/min, $f = 0.1$ mm/rev)
3.2 Cutting of brass alloy material

Force measurements

For brass alloy material the increase of the cutting conditions (v, a, and f) causes the increase of \( F_t \) and \( F_r \) components for both cases of CT and UAT as stainless steel alloys as shown in figures 15-17. It can be noticed that in case of UAT the cutting forces is lower than that in case of CT. At cutting speed \( v = 45 \text{ m/min} \) as example for comparison between CT and UAT. It can be found that \( F_t \) decreased by 61.5% while \( F_r \) decreased by 80.3% while at depth of cut \( a = 0.3 \text{ mm} \) the cutting forces \( F_t \) decreased by 85.2% while \( F_r \) decreased by 31.9%.

Figure 15. Effect of cutting speed (v) on the tangential cutting force (\( F_t \)) (a) and radial cutting force (\( F_r \)) (b) for turning of brass under CT and UAT (f = 0.2 mm/rev, a = 0.3 mm)

Figure 16. Effect of depth of cut (a) on the tangential cutting force (\( F_t \)) (a) and radial cutting force (\( F_r \)) (b) for turning of brass under CT and UAT (v = 35 m/min, f = 0.1 mm/rev)
Figure 17. Effect of feed rate ($f$) on the tangential cutting force ($F_t$) (a) and radial cutting force ($F_r$) (b) for turning of brass under CT and UAT ($v = 45$ m/min, $a = 0.3$ mm)

As can be detected from figures 18-20, UAT causes improvements of surface quality where $R_a$ and $S_a$ at $v = 45$ m/min decreased by 23.1% and 17.5% respectively. While at $a = 0.4$ mm, $R_a$ and $S_a$ decreased by 33.6% and 9.6%. But for $f = 0.2$ mm/rev causes the decrease of $R_a$ and $S_a$ by 23.1% and 17.5%.

Figure 18. Effect of cutting speed ($v$) on the average roughness ($R_a$) (a) and average roughness ($S_a$) (b) for turning of brass under CT and UAT ($f = 0.2$ mm/rev, $a = 0.3$ mm)

Figure 19. Effect of depth of cut ($a$) on the average roughness ($R_a$) (a) and average roughness ($S_a$) (b) for turning of brass under CT and UAT ($v = 35$ m/min, $f = 0.1$ mm/rev)
Figure 20. Effect of feed rate ($f$) on average roughness ($R_a$) and average roughness ($S_a$) for turning of brass under CT and UAT ($v = 45$ m/min, $a = 0.3$ mm)

It can be deduced that UAT causes also the decrease of out of roundness as a measure of machining accuracy for brass material as in figures 21-23; at $v = 45$ m/min, $R_o$ decreased by 30.6%, while at $a = 0.3$ mm, $R_o$ decreased by 30.4%, but at $f = 0.1$ mm/rev, $R_o$ decreased by 44.3%.

Figure 21. Effect of cutting speed ($v$) on out of roundness ($R_o$) for turning brass under CT and UAT ($f = 0.2$ mm/rev, $a = 0.3$ mm)

Figure 22. Effect of depth of cut ($a$) on out of roundness ($R_o$) for turning brass under CT and UAT ($v = 35$ m/min, $f = 0.1$ mm/rev)

Figure 23. Effect of feed rate ($f$) on the out of roundness ($R_o$) for turning of brass under CT and UAT ($v = 45$ m/min, $a = 0.3$ mm)

3.3. Empirical relationships

For machining the SS work piece some empirical formulas as in equations 1-4 can be deduced by curve fitting of the obtained experimental data, for CT to deduce the tangential $F_t$ and radial $F_r$ cutting
force components as follows:

\[ F_t = 2461.6 \times v^{-0.1482} \times a^{1.2015} \times f^{0.4636} \]  
\[ F_r = 42.59 \times v^{0.9323} \times a^{1.1398} \times f^{0.541} \]

The respective expressions for UAT have the following form:

\[ F_t = 2737.1 \times v^{-0.1629} \times a^{1.7271} \times f^{0.6072} \]  
\[ F_r = 3.365 \times v^{1.5305} \times a^{1.2054} \times f^{0.5848} \]

Here \( v \) is the cutting speed in m/min, \( a \) the depth of cut in mm, and \( f \) is the feed rate mm/rev, where the above formula is valid in the cutting conditions ranges obtained in the present research. A comparison of the calculated values using the above formula with the obtained experimental data is shown in figures 24-25.

![Figure 24](image-url)  
**Figure 24.** Calculated and measured tangential \((F_t)\) (a) and radial \((F_r)\) (b) force components under CT for SS specimen

![Figure 25](image-url)  
**Figure 25.** Calculated and measured tangential force\((F_t)\) (a) and radial \((F_r)\) (b) components under UAT for SS specimens

4. **Conclusions**

Based on the undertaken experimental analysis of two turning techniques, it can be concluded that:

a. The tangential and radial components of the cutting force in case of UAT are lower than those in
CT for both studied materials: stainless steel and brass.
b. The average surface roughness in case of UAT is lower than that in case of CT in both materials.
c. The out of roundness as a measure of machining accuracy in case of UAT is lower than that in case of CT in both materials.
d. Empirical relationships were suggested for the tangential and radial components under UAT and CT for stainless steel material.

References
[1] Nath C and Rahman M 2008 Effect of machining parameters in ultrasonic vibration cutting. *Int. J. Machine Tools Manuf.* **48**(9) 965-974
[2] Pujana J, Rivero A, Celaya A and López de Lacalle L 2009 Analysis of ultrasonic-assisted drilling of Ti6Al4V *Int. J. Machine Tools Manuf.* **49**(6) 500-508
[3] Nath C, Rahman M and Neo K S 2009 Machinability study of tungsten carbide using PCD tools under ultrasonic elliptical vibration cutting *Int. J. Machine Tools Manuf.* **49**(14) 1089-1095
[4] Shamoto E, Suzuki N and Hino R 2008 Analysis of 3D elliptical vibration cutting with thin shear plane model *CIRP Annals – Manuf. Technol.* **57**(1) 57-60
[5] Mitrofanov A, Ahmed N, Babitsky V and Silberschmidt V V 2005 Effect of lubrication and cutting parameters on ultrasonically assisted turning of Inconel 718 *J. Mater. Process. Technol.* **162**–**163** 649-654
[6] Voronina S and Babitsky V 2008 Autoresonant control strategies of loaded ultrasonic transducer for machining applications *J. Sound Vibrat.* **313**(3–5) 395-417
[7] Amini S, Soleimanimehr, H, Nategh M, Abudollah A and Sadeghi M 2008 FEM analysis of ultrasonic-vibration-assisted turning and the vibratory tool *J. Mater. Process. Technol.* **201**(1–3) 43-47
[8] Nath C, Rahman M and Neo K S 2009 A study on the effect of tool nose radius in ultrasonic elliptical vibration cutting of tungsten carbide *J. Mater. Process. Technol.* **209**(17) 5830-5836
[9] Mitrofanov A, Babitsky V and Silberschmidt V V 2003 Finite element simulations of ultrasonically assisted turning *Comput. Mater. Sci.* **28**(3-4) 645-653
[10] Li X and Zhang D 2006 Ultrasonic elliptical vibration transducer driven by single actuator and its application in precision cutting *Journal of Materials Processing Technology*, **180**(1-3) 91-95
[11] Brehl D and Dow T 2008 Review of vibration-assisted machining *Precision Engng* **32**(3) 153-172
[12] Babitsky V, Kalashnikov A, Meadows A and Wijesundara A 2003 Ultrasonically assisted turning of aviation materials *J. Mater. Process. Technol.* **132**(1-3) 157-167
[13] Babitsky V, Mitrofanov A, and Silberschmidt V V 2004 Ultrasonically assisted turning of aviation materials: simulations and experimental study *Ultrasonics*, **42**(1-9) 81-86
[14] Moriwaki T and Shamoto E 1995 Ultrasonic elliptical vibration cutting. *CIRP Annals – Manuf. Technol.* **44**(1) 31-34
[15] Shamoto E, Suzuki N, Moriwaki T and Naoi Y 2002 Development of ultrasonic elliptical vibration controller for elliptical vibration cutting. *CIRP Annals – Manuf. Technol.* **51**(1) 327-330
[16] SECO Group, 2012, SECO DNMG insert, SECO tools media catalogue p 19, Retrieved September 2012, www.secotools.com/gb
[17] S.R.C. Effect of ultrasonic vibration on the turning process 1969 *Int. J. Machin. Tool Design Res.* **9**(4) 363-374