Article:

Maurotto, A. and Wickramarachchi, C. (2016) Experimental investigations on effects of frequency in ultrasonically-assisted end-milling of AISI 316L: a feasibility study. Ultrasonics, 65. 113 - 120. ISSN 1874-9968

https://doi.org/10.1016/j.ultras.2015.10.012

Experimental investigations on effects of frequency in ultrasonically-assisted end-milling of AISI 316L: a feasibility study.

A. Maurotto [a,*], C.T. Wickramarachchi [b]

[a] Nuclear AMRC, The University of Sheffield, Brunel Way, S60 5WG Catcliffe, U.K..

[b] Aerospace Engineering, The University of Sheffield, Sir F. Mappin building, S1 3JD Sheffield, U.K..

[*] Corresponding author's email: a.maurotto@namrc.co.uk ; phone: +447908996086

Abstract: The effects of frequency in ultrasonic vibration assisted milling (UVAM) with axial vibration of the cutter is investigated in this paper. A series of face-mill experiment in dry conditions were conducted on AISI 316L, an alloy of widespread use in industry. The finished surfaces roughness were studied along with basic considerations on tool wear for both conventional milling and an array of frequencies for UVAM (20-40-60 kHz) in a wide range of cutting conditions. Surface residual stresses and cross-cut metallographic slides were used to investigate the hidden effects of UVAM.

Experimental results showed competitive results for both surface roughness and residual stress in UVAM when compared with conventional milling especially in the low range of frequency with similar trend for tool wear.

Keywords: Vibration cutting; Dry milling; End milling; Ultrasonic; Surface integrity; Residual stress

1 Introduction

Manufacturing work-pieces with high surface integrity has become greatly significant as modern components are required to withstand service for longer times. Aggressive environments, strenuous fatigue cycles and high temperatures are to be expected in recent applications and require components to be manufactured accordingly. Austenitic stainless steels present the desired corrosion resistance and ductility to fit most challenging industrial applications. In particular, AISI 316L alloy, presents high ductility and resistance to corrosion in chemically aggressive solutions.

Machining of AISI 316L is complicated by its low thermal conductivity and high ductility. Cutting fluids are recommended when machining this alloy. However, in recent years the current trends in manufacturing have started to move from traditional use of flood cutting fluids to minimal quantity lubrication and dry cutting primarily due to environmental concerns. Cost associated to cutting fluids adequate disposal represents a large amount of the machining-associated expenditure with some research claiming they overtake the costs of cutting tools [1]. Running costs associated with cutting fluids represent a significant fraction of overall manufacturing expenditure [2] so that their elimination or reduction represents a significant economic incentive for the industry. In this sense, dry machining is a valuable alternative which addresses the needs for competitive cost reduction and environmental concerns [3]. Dry cutting is, however, not suitable in several application that require high accuracy of the finished components or high surface integrity.

Vibration-assisted machining while well known for decades has only recently been introduced in the milling manufacturing industry by DMG-Mori Seiki. In this cutting method vibrations at a frequency above the audible range are superimposed on the cutting tool with a specific intensity and in a specific direction. Vibration assisted machining has been widely used for machining the most diverse work-piece materials often with significant improvements observed [4].

Noticeable effects on the elastic-plastic behavior of the work-piece material when subjected to the ultrasonic field are documented. Contact friction between tool and work-piece is believed to transform into quasi-viscous friction in presence of ultrasonic vibration [5]. Shamoto [6,7] and Babitsky [8,9] early works demonstrated the capabilities of the technique and pawed the way for a widespread adoption of ultrasonically-assisted machining. Several researchers reported advantages in ultrasonically-assisted machining when comparing results with similar conventional techniques.

Ultrasonically-assisted machining was shown to have beneficial effects on the average cutting force with significant reductions in excess of 50% [10] and reaching up to 80% in particular conditions [11,12]. Cutting force effects were most pronounced when vibrations were imposed on the tool in the same direction of cut [4]. Subsequently consistent reductions of regenerative chatter were observed with large improvements of the surface of finished work-pieces [13,14]. A significant impact on surface residual stresses was also observed in hard or difficult-to-machine alloys in a wide range of cutting conditions in oblique and orthogonal turning [15,16].

Surface quality was observed to improve when comparing vibration aided turned or milled specimens with conventionally manufactured ones [17,18] as a result of improved behavior of material under high-strain regime [19,20,21,22].

Ultrasonically-assisted machining is already consistently delivering better performance in turning and drilling, however little knowledge is available on milling. In this paper a design-of-experiment systematic characterization of AISI316L in UVAM is presented with particular regards to the effects of vibration frequency and cutting parameters on the finished specimens.

2 Experimental procedure

2.1 Experimental setup

In this study a 5-axis CNC milling machine was used (US10 DMG-Mori Seiki) in a 3-axis configuration. This machine presents limitation in power and torque (7.7 kW; 2 Nm) and maximum 40x20 mm work-pieces can be installed on the machine bed (Figure 1). This limits the maximum material removal rate to the micro-machining range.

The spindle of the machine is monolithic and comprises the piezo-electric actuator, concentrating horn and tool holder. It is powered inductively by a transmitter coil (fixed on the machine) and a receiver coil (rotating co-axially with the spindle). Vibration are generated by the piezo-actuator in a co-axial direction to the axis of the spindle. Maximum displacement is amplified by the horn before being transferred to the cutting tool. Table 1 presents the maximum specifications of the US10 machine.

Table 1: Milling machine maximum specifications

Power	7.7 kW
Spindle rotation speed	40000 rpm
Combined feed	10 m/min
Tool holder capacity	7 mm
Torque	2 Nm
Vibration frequency	80 kHz
Displacement amplitude	11 μm

A cemented carbide tool was selected for the machining experiments aiming for it to be usable in both conventional and ultrasonic mode. Such a tool, not designed specifically to improve machinability in UVAM, would not significantly impact results hence making the identification of effects easier to identify. A Sandvik Coromant CoroMill Plura solid carbide square shoulder end-mill was chosen as coated carbide tools are normally used in the machining of austenitic steels. This tool is optimised for finish cuts and has a tough micro-grain structure suitable for intermittent cutting which should withstand the micro-impact cutting regimen of UVAM.

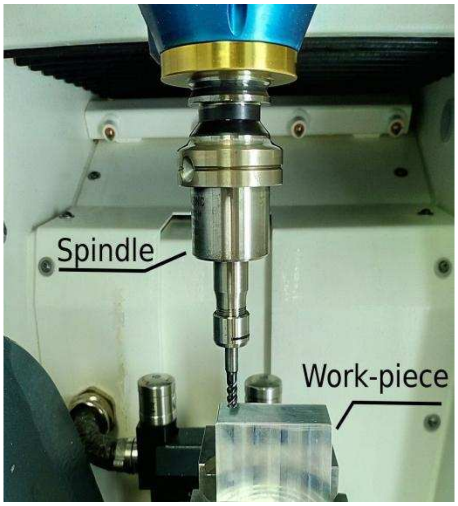


Figure 1: The machining setup

The tool coating consists of a PVD ceramic layer of titanium-aluminium nitride. Presence of aluminium in the coating material leads, at high temperatures, to the formation of an aluminium oxide (alumina) layer which increases hot hardness and resistance to wear. Tools were shortened to a 40 mm overall length from the original size of 57 mm to increase stiffness and reduce spurious vibrations induced by the flexibility of the tool.

Table 2 shows a summary of the characteristics of this tool.

Table 2: Cutting tool specifications

Axial rake	10.5°
Cutting diameter	5 mm
Maximum depth-of-cut	8 mm
Cutting edges	4
Corner radius	0.5 mm
Coating	TiAlN (PVD)

2.2 Work-piece material

The work-piece material used in the work belongs to the 3XX austenitic stainless family. This class of materials show high ductility with significant elongation at breakage (45%) and low yield stress. The alloy presents almost completely a cubic face centered austenite phase with traces of ferrite inclusion. Its mechanical properties are summarised in table 3.

Table 3: Mechanical properties of work-piece material.

Work-piece material	AISI 316L (X2CrNiMo17/12/2)
Work-piece size	38x18x18 mm trapezoidal
Producer	Acroni
Conditions	Rolled plates
Young's modulus E (GPa) at room temperature	200
Density, ρ (kg/m^3)	8027
Thermal conductivity, k (W/mk)	14.6
Ultimate tensile strength, σ_{u1} (MPa)	620

2.3 Experimental methodology

To easily characterise the response of the material to the variation of the key process variable (KPV) a simplistic design of experiment (DoE) was used. The design of experiment incorporated three KPV: cutting speed, feed per tooth and vibration frequency. The range of cutting parameters was selected to be within the tool manufacturer recommended values. Two continuous variables, namely cutting speed and feed-per-tooth, were sub-divided into three values each: low, mid and high as shown in Table 4 and implemented into the DoE. Combination of those values created a 3x3 matrix of experiments which was repeated for each vibration frequency (0, 20 kHz, 40 kHz, 60 kHz) resulting in 36 experiments [Table 4]. Four additional experiments were performed to evaluate the variance of the responses bringing the tests total to 40.

Table 4: Key process variables matrix.

Cutting speed [rpm]	Feed per tooth [mm/th]		
1500 (23.56 m/min)	0.011	0.022	0.033
2000 (31.41 m/min)	0.00825	0.0165	0.02475
2500 (39.27 m/min)	0.0066	0.0132	0.0198

Experiments were randomised in iso-frequencies blocks to avoid interferences on the responses such as those caused by machine operator or tool wear. To further reduce tool wear related effect a new tool was used each time the frequency was varied (every block of 9 runs) with the additional mixed four experiments being performed with one new tool.

Analysis of the result was carried out with Umetrics software Modde 10.1.1 using the multiple linear regression method capable of accounting for interactions between the cutting parameters.

Two quantitative responses were evaluated for each test, namely surface roughness and surface residual stress. Surface roughness was evaluated by a Mitutoyo Surftest SJ-410 stylus instrument.

Residual stress measurements were carried out on a Proto iXRD combo residual stress analyser, fitted with a Mn-Kα tube and operating at 20 KV, 4 mA. A collimator with a 2mm circular aperture was used to measure the (311) austenite peaks, that were fitted with a Gaussian function.

Surface effects were evaluated by Scanning Electron Microscopy (SEM) slides to investigate cutting tool markings and micro-patterns on the machined surface of the coupons. Samples were thoroughly cleaned by first washing them with propan-2-ol and then by an ultrasonically agitated acetone bath. They were then handled with gloves to prevent contamination. Analyses were performed on a Carl Zeiss EVO LS25 scanning electron microscope.

Cross-cut metallographic microscopic slides were prepared to asses the hidden effects of UVAM on the sub-surface layers. Coupons were cut and polished, etched with glyceregia solution and neutralised before being observed on a Leica DM-IRM optical microscope.

A summary analysis of the tool wear was performed on the SEM by visual inspection of the cutting edge and quantitative evaluation with ImageJ sofware of the tool damage length and areas.

3 Results

In this section the experimental results obtained in conventional and UVAM machining are presented. Quantitative responses precede qualitative ones: first we report on the experimentally obtained surface roughness and surface residual stresses. Subsequently, surface SEM slides and metallographic sub-surface analysis complete the investigations on the work-piece. Last, a brief analysis of the tool damage is presented.

3.1 Surface roughness

For each machined surface, five areas results were averaged to reduce the influence of inhomogenities in the material or accidental damage on the measured roughness. The standard deviation of the measures was used to evaluate the quality of the data.

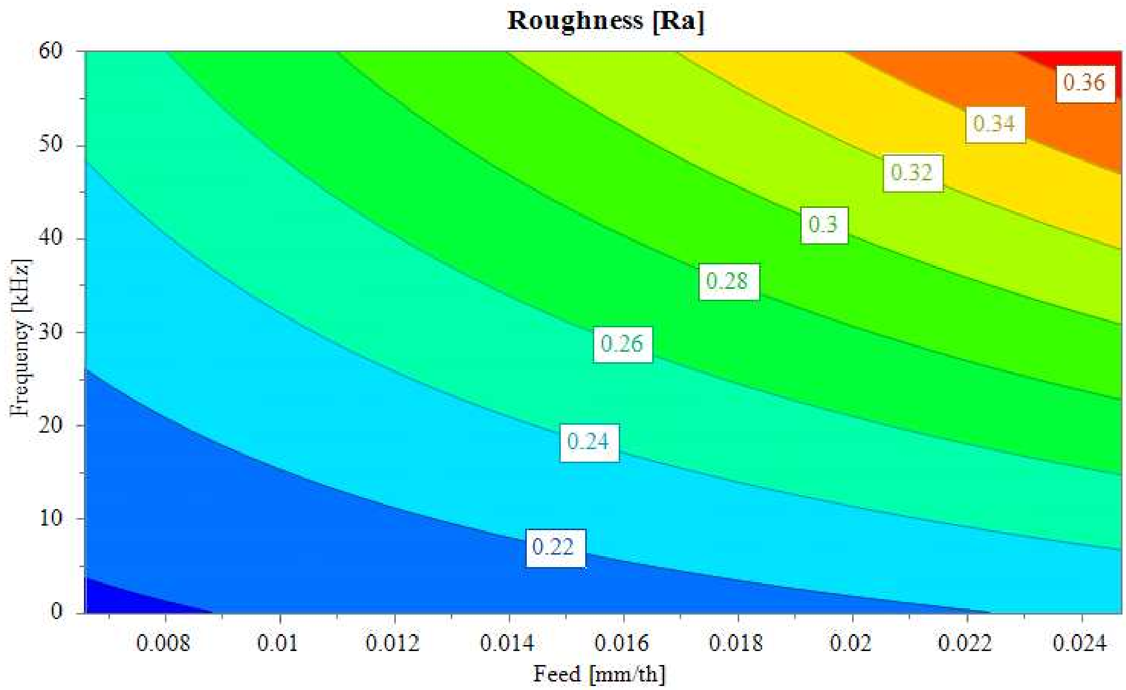


Figure 2: Surface roughness of surfaces machined versus frequency and feed

In Figure 2 surface roughness appears slowly varying with feed, appearing to be increasing with it. Interestingly, UVAM always results in slightly worse roughness than conventional milling, with quality degrading with an increase in the frequency of the vibration.

It is worth to be noted, however, that surface roughness remained excellent in both conventional and UVAM experiments.

Results appeared to be independent, within the statistical error, from the cutting speed.

3.2 Residual stress

Similar methodology to the one used for surface roughness was used for measuring the surface residual stresses. Longitudinal, transverse and 45° stresses were measured on the finished surfaces. Due to space constrains, only the maximum stress is reported in this work. Notably, measured stresses were compressive for all test specimens and appeared to depend strongly on feed. Effects of frequency were more subtle and complex with the lowest compressive stress measured at 40 kHz for all the cutting parameters taken into account (Figure 3).

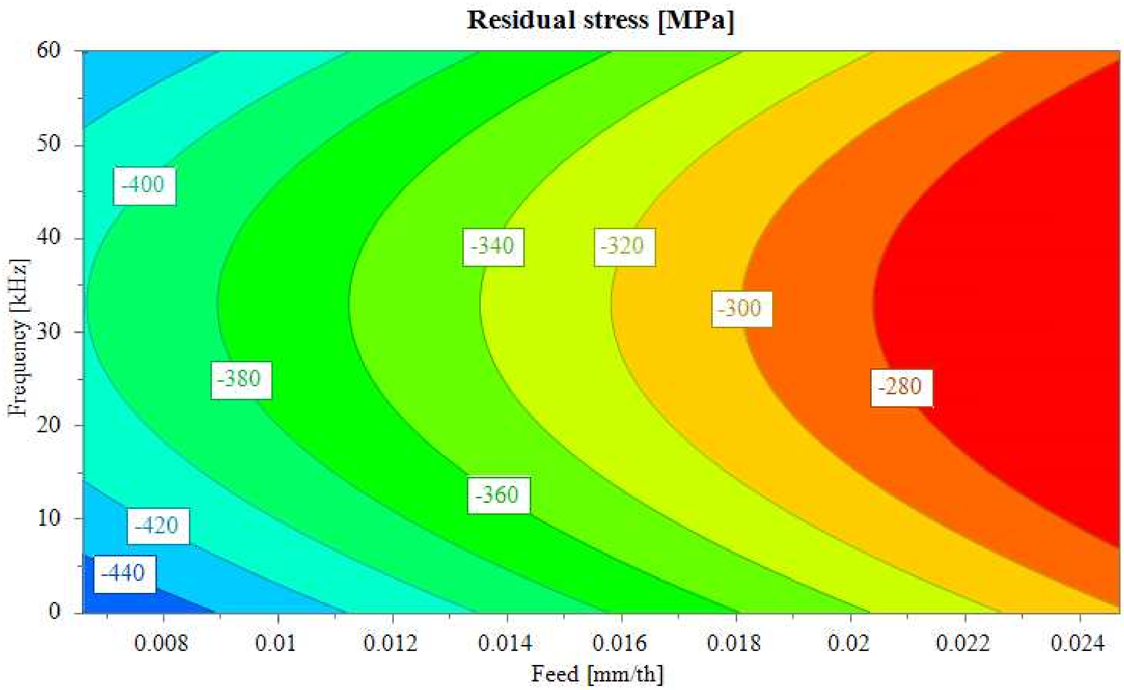
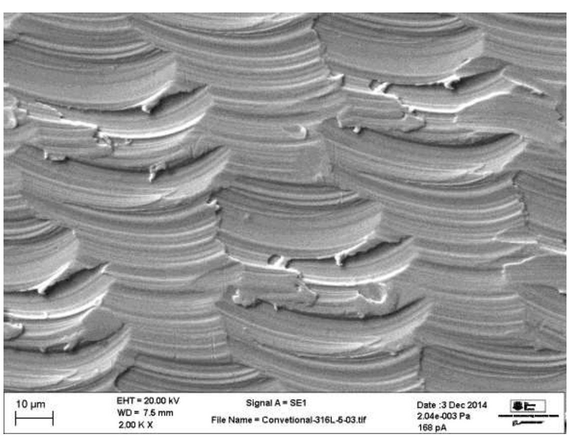
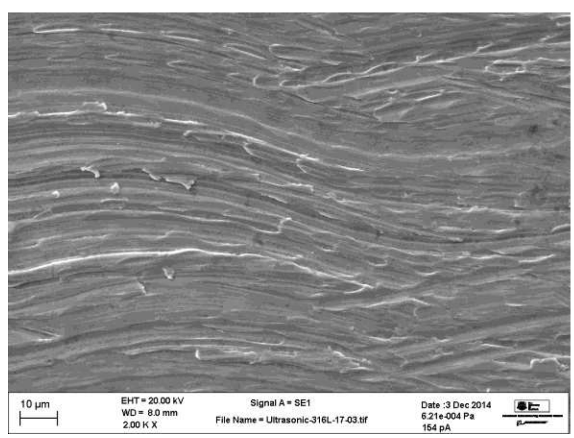


Figure 3: Surface residual stresses measured against cutting speed and feed

3.3 Surface topology at the SEM and optical metallography

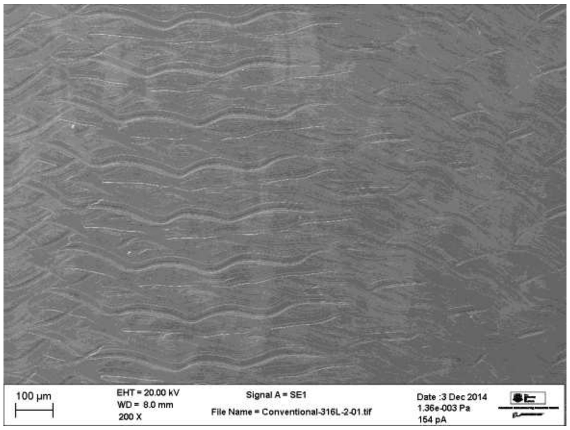
High magnification SEM pictures showed the density of cutting tool marks left on the surface of the work-piece increasing, as expected, with vibration frequency. The slides in Figure 4 shows how the shape and quantity of tool marks differs with increasing the vibration frequency and keeping the other cutting parameters constant. In particular the sample machined at 40 kHz appeared visibly different from all the other UVAM machined and more similar to the conventionally machined one. By increasing the magnification additional details were resolved. Figure 3 shows a comparison between a conventionally milled sample and one machined in UVAM. The latter showing signs of the micro-chipping character of the ultrasonic technique.

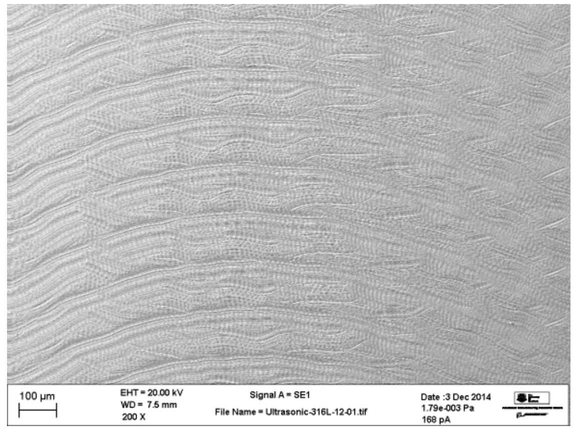




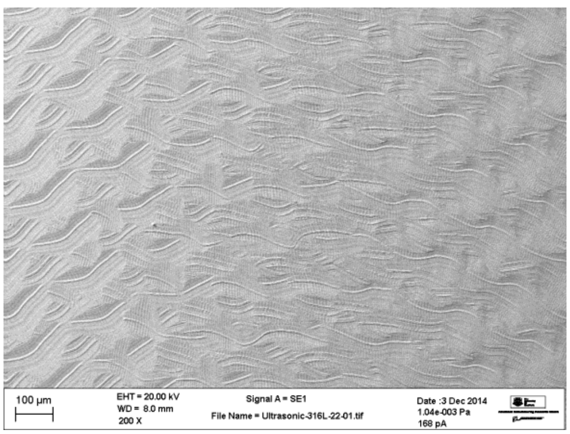
a) b)

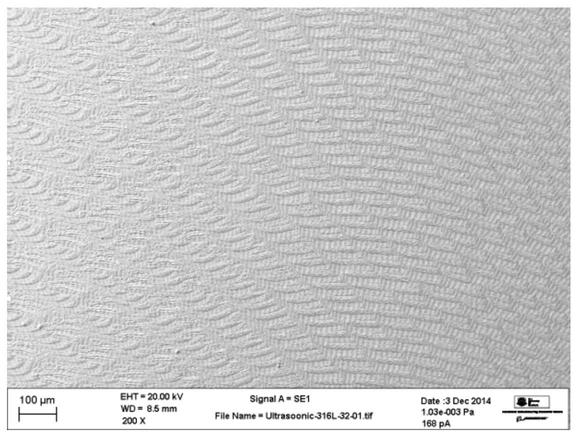
Figure 4: SEM close up of surface structures machined: a) conventionally; b) at 20 kHz vibration.





a) b)



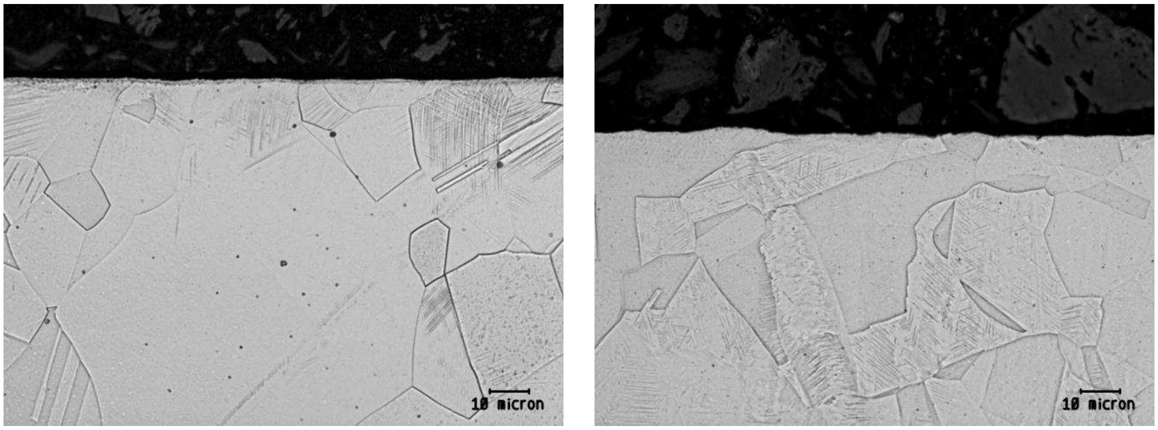


c) d)

Figure 5: SEM images of surfaces machined respectively: a) conventionally; b) at 20 kHz; c) at 40 kHz; d) at 60 kHz.

In both Figure 3 and 4 was possible to appreciate the higher density of tool marking left on the surface when ultrasonic vibration was superimposed during the cutting process. It was also possible to identify a tendency to smearing and smudging effects on the material cut with UVAM.

Cross-cut sub-surface metallography slides did not show significant differences between work-pieces machined with conventional milling and the ultrasonically-assisted ones. Figure 5 shows the grain structure in the layers immediately below the surface. It is visible how structures are virtually the same in conventionally and ultrasonically machined work-pieces. Grain sizes appeared comparable and there was an absence of grain rotations, grain refinements or strongly deformed areas indicating significant machining abuse. In fact, slides showed an almost undisturbed grain structure.



a) b)

Figure 6: Cross-cut metallography slides for: a) conventionally and b) 20 kHz ultrasonically machined coupons.

3.4 Tool damage characterisation

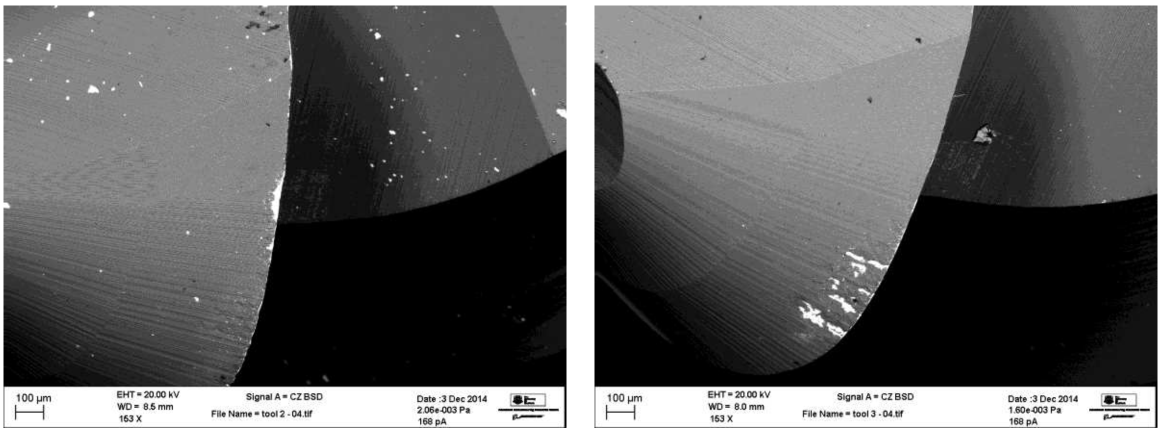
Four tools in total were used during the machining trials and each tool was dedicated to a single frequency in order to isolate its effects on tool wear or damage. Each tool cutting edge was analysed at the SEM. Tool damage, crater and flank wear were assessed. Chipping style damage of the cutting edge was maximum in the tool used for conventional machining and the one used with 60 kHz vibration, while the tool used to machine at 20 kHz showing the least damage. Significant crater wear was found in the tool used in conventional milling along with marginal findings for the one used at 60 kHz vibration. Flank wear was only observed on the tool used to machine with vibration at 40 kHz and represented the largest wear finding among all the other tools.

Table 5 illustrates quantitative results for tool wear obtained with ImageJ software on optical and SEM slides. The average length of edge damage is similar for conventional, 40 kHz and 60 kHz tools with a significant reduction for the 20 kHz tool. The average damaged area on cutting edges appears to be following the same trend with the noticeable exception of the 40 kHz tool showing large areas of coating loss.

Table 5: Quantitative tool wear characterisation

	Tools			
Tool wear	Conventional	20 kHz	40 kHz	60 kHz
Average damaged area [μm^2]	19000	16000	80000	20000
Average length of damage [μm]	490	340	460	450

Figure 6 compares the tool damage observed in in UVAM at 20 kHz with the one observed at 40 kHz. The 40 kHz vibration appeared to produce the maximum damage. Damaged area on the conventional tool was as well significantly larger than the one of the 20 kHz UVAM one. Lengths of damage affected edge were similar for each tool with the notable exclusion of the tool used to machine at 20 kHz vibration that presented a reduction of approx 30% when compared to the tool used to machine conventionally. Largest worn areas was observed for the tool used to machine at a frequency of 40 kHz with over 80% damaged area increase when compared to the 20 kHz one.



a) b)

Figure 7: UVAM tool damage comparison: a) 20 kHz b) 40 kHz

6 Discussion

Effects of ultrasonic vibration are strongly dependent on the angle formed between the vibration direction and the cutting speed [5] with most noticeable effects happening when vibration angle and cutting speed are aligned. In the DMG-Mori Seiki design, the vibration are generated along the axis of the cutting tool, they are, therefore, always orthogonal to the cutting speed vector. In this work, the cutting speed variation (23.5-39.3 m/min) was not statistically large enough to induce a response above the noise level in both surface roughness and residual stresses. The small variation of the cutting speed in respect to the high-frequency low-amplitude vibration had no statistically measurable effects ,thus indicating a lack of complete separation between the tool and the work-piece [5,20]. Previous studies did observe a rather small effects of cutting speed on roughness especially in the case of small vibration amplitude (~2 μm) at slow cutting speed [23]. Results were, however, not comparable with our case since vibration amplitude and cutting speed were significantly lower. Machine generated vibration amplitude was also expected to very between frequencies, with progressive reduction of displacement toward the high end of the vibratory range yet variations observed were minimal in the frequency range studied.

A desirable compressive stress field was observed on the machined surface in all tests. Compressive residual stresses are known to increase resistance of the material to cracking ultimately resulting in enhanced corrosion resistance. Test results indicated how the frequency of 40 kHz appeared to produce slightly worse results than the frequency of 20 and 60 kHz in the residual stress field [Figure 7].

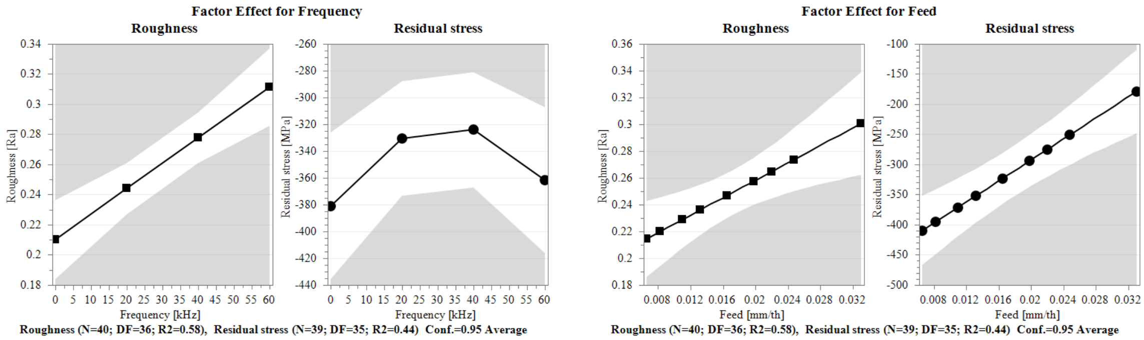


Figure 8: Influence of frequency and feed on qualitative responses.

This finding could be the sign of a spurious vibratory mode at this frequency, which could influence the cutting process causing less-than-optimal cutting conditions. These machining conditions create higher cutting temperatures which in turn increase the tensile component of the stress field ultimately reducing the magnitude of compressive stresses measured on the surfaces.

Surface roughness, however, did not appear to be affected by the same phenomena and was shown to monotonically increase with increasing frequency. This being a probable result of the higher density of tool marks observed at higher vibration frequency [Figure 4] [24].

Material smudging effects in UVAM, as observed in Figure 3b, could be explained by the increased apparent ductility of the alloy. It would be likely be caused by a shift in the visco-elasto-plastic properties of the material and by the localised temperature increase due to the additional vibration energy [25]. Additionally, vibration of the tool apparently increased the cutting edge radius, subsequently generating more ploughing effects on the immediate surface.

Feed effects on surface roughness and residual stresses appeared to be proportional to the feed-per-tooth. Higher feed rates significantly reduced surface quality. As average chip thickness increased more aggressive machining conditions were achieved resulting in a reduced surface quality. Tool marks on the surface became deeper and more spaced between each other ultimately increasing the R_a values.

Effects on residual stress were similar, with a progressive reduction of the residual compressive field with increasing feed-per-tooth. This was expected as the increase in the average chip thickness created a larger interaction volume between the tool and the chip, thus increasing the cutting force necessary to remove the material. Higher amount of heat generated when removing a larger chip created tensile stresses on the surface which counterbalanced the compressive ones [26].

Effects of frequency and feed on surface roughness and residual stress appeared to be non-linear with presence of a complex interaction between each other. This was to be expected in a non-linear process such as UVAM.

Significant surface differences between UVAM and conventionally machined specimens were observed at the SEM. Tool markings shape and density changed accordingly to frequency indicating the co-existence of different vibratory modes in the range of frequencies studied in this work. In particular the vibration frequency of 40 kHz appeared to produce surface marking similar to the one observed in conventional milling. Increasing suspicion that the vibratory mode at 40 kHz was different than the ones at 20 and 60 kHz. Micro structures observed on UVAM machined surfaces appeared likely to present a different lubricant retention when compared with conventionally milled ones [Figure 4].

It is known that ultrasonically-assisted machining generates higher-than-normal temperatures in the cutting zone [16]. Considered the low thermal conductivity of AISI316L it was deemed necessary to investigate the sub-surface layers of the finished work-pieces in search of phase changes or other additional indicators of thermal abuse. Phase changes are particularly undesirable in this alloy as they compromise the ductility and corrosion resistance of the austenitic phase. No visible changes were observed in the UVAM machined work-pieces [Figure 5]. It is, therefore, safe to claim that no phase transformation are expected at the studied depth-of-cut, cutting speed and feed. In particular, vibration frequency did not appear to influence the sub-surface layer structure of austenitic grains for all frequencies taken into account. This indicating the reduced likelihood of undesired strain-induced α' martensite or strong grain refinement effects.

Brief considerations on tool damage and wear allowed us to identify the frequency of 40 kHz as the least suitable for achieving a reasonable tool life for this particular tool (see Table 5). While the frequency of 20 kHz was shown to surprisingly enhance tool life even when compared to conventional milling. It was expected, in fact, that ultrasonic vibration would affect tool life by accelerating fatigue failure [27]. Among the other expected effects there was breakage when chip adhered to the tool. Carbide tools are, in fact, quite brittle and resistant to compressive stresses but tend to be rather weak against tensile ones. In the case of UVAM adhesion of the chip to the cutting edge could subject the tool to high tensile stresses ultimately causing its premature failure [28]. Higher-than-normal thermal effects expected in UVAM could facilitate chip adhesion to the rake face of the tool. For the frequencies evaluated in this work built-edge and chip-adhesion did not appear to directly influence tool life. An abnormal amount of damage was shown only the tool used to machine at 40 kHz. This was deemed consistent with an incorrect engagement between tool and work-piece. It should be noted, however, that tool wear and tool response to ultrasonic vibration are strongly dependent on tool geometry, material and coating and it is not possible to assume a different cutter would exhibit the same behavior.

5 Conclusions

In this paper, we studied effects of the vibration frequency on the surface roughness, residual stress and grain structure of the machined work-pieces when using “depth-of-cut direction” (axial) ultrasonically-assisted end milling at micro-machining conditions. In particular, it was possible to summarise the major conclusion of this study as follows:

- UVAM machined work-pieces did not appear to exhibit significant adverse effects when compared to conventionally machined ones, yet a measurable increase in roughness was observed.
- Analysis of the sub-surface layer didn’t underline any deformation-related phase change or significant grain structure modification for UVAM.
- Surface integrity and residual stress, while varying between different frequencies, changed within a narrow range and remained always excellent.
- Tool wear appeared to be sensitive to vibration frequency, and showed damage mechanism which did not appear related to fatigue. Coating damage was the predominant form of wear observed.

According to the experimental results UVAM generates much finer surface structures and more uniform surfaces. It should be noted that even if UVAM could be considered a micro-chipping process, initial observations demonstrated that tool life could even be extended when compared with conventional milling. However, limitation on the maximum tool diameter greatly reduced the choice of tooling that was possible to install in the machine. Perhaps is worth noting that special tools are generally required in vibration-assisted cutting, and probably the expectation of using conventional tool is demanding. Experimental investigations on the vibratory mode of the tool at different frequencies and higher resolution surface cross-cut section will be carried on in the future for different classes of materials.

Acknowledgments

UK’s Engineering and Physical Sciences Research Council (EPSRC) under the NNUMAN (New NUclear MANufacturing) research programme (EP/J021172/1) funding is acknowledged. The authors would like to acknowledge Sandvik Coromant and DMG-Mori Seiki for obtaining access to their equipments, and provision of assistance by their staff.

References

[1] F. Klocke, G. Eisenblätter, T. Krieg, Machining: wear of tools, second ed., in: Encyclopaedia of Materials: Science and Technology, 2001.

[2] G. Byrne, E. Scholta, Environmentally clean machining processes - A strategic approach, CIRP Annals - Manufacturing Technology 42 (1993) 471-474.

[3] P.T. Mativenga, M.F. Rajemi, Calculation of optimum cutting parameters based on minimum energy footprint, CIRP Annals - Manufacturing Technology 60 (2011) 149-152.

[4] D.E. Brehl, T.A. Dow, Review of vibration-assisted machining, Precision Engineering 32 (2008) 153-172.

[5] V.K. Astashev, V.I. Babitsky, Ultrasonic cutting as a nonlinear (vibro-impact) process, Ultrasonics 36 (1998) 89-96.

[6] E. Shamoto, T. Moriwaki, Ultaprecision Diamond Cutting of Hardened Steel by Applying Elliptical Vibration Cutting, · CIRP Annals - Manufacturing Technology 48 (1999) 441-444.

[7] T. Moriwaki, E. Shamoto, Y.C. Song, S. Kohda, Development of a Elliptical Vibration Milling Machine, · CIRP Annals - Manufacturing Technology 53 (2004) 341-344.

[8] V.I. Babitsky, A.V. Mitrofanov, V.V. Silberschmidt, Ultrasonically assisted turning of aviation materials: simulations and experimental study, Ultrasonics 42 (2004) 81–86.

[9] V.I. Babitsky, V.K. Astashev, A. Meadows, Vibration excitation and energy transfer during ultrasonically assisted drilling, Journal of Sound and Vibration 308 (2007) 805–814.

[10] A. Sharman, P. Bowen, D. Aspinwall, C. Dewes, Ultrasonic Assisted Turning of Gamma Titanium Aluminide, Rolls-Royce PLC, 2001.

[11] A. Maurotto, R. Muhammad, A. Roy, V.V. Silberschmidt, Enhanced ultrasonically assisted turning of a b-titanium alloy, Ultrasonics 53 (2013) 1242-1250.

[12] R. Muhammad, A. Maurotto, A. Roy, V.V. Silberschmidt, Ultrasonically assisted turning of Ti-6Al-2Sn-4Zr-6Mo, Journal of Physics: Conference Series 382 (2012).

[13] M. Xiao, K. Sato, S. Karube, T. Soutome, The effect of tool nose radius in ultrasonic vibration cutting of hard metal, International Journal of Machine Tools and Manufacture 43 (2003) 1375-1382.

[14] C. Nath, M. Rahman, S.S.K. Andrew, A study on ultrasonic vibration cutting of low alloy steel, Journal of Materials Processing Technology 192-193 (2007) 159-165.

[15] A. Maurotto, C. Siemers, R. Muhammad, A. Roy, V.V. Silberschmidt, Ti Alloy with Enhanced Machinability in UAT Turning, Metallurgical and Materials Transactions A 45 (2014) 2768-2775.

[16] R. Muhammad, S. Hussain, A. Maurotto, C. Siemers, A. Roy, V.V. Silberschmidt, Analysis of a free machining α+β titanium alloy using conventional and ultrasonically assisted turning, Journal of Materials Processing Technology 214 (2013) 906-915.

[17] X.H. Shen, J.H. Zhang, T.J. Yin, C.J. Dong, A study on cutting force in micro end milling with ultrasonic vibration, Advanced Materials Research 97-101 (2010) 1910-1914.

[18] V.V. Silberschmidt, S.M.A. Mahdi, M.A. Gouda, A. Naseer, A. Maurotto, A. Roy, Surface-roughness improvement in ultrasonically assisted turning, Procedia CIRP 13 (2014) 49-54.

[19] N. Ahmed, A.V. Mitrofanov, V.I. Babitsky, V.V. Silberschmidt, 3D finite element analysis of ultrasonically assisted turning, Computational Materials Science 39 (2007) 149–154.

[20] R. Muhammad, N. Ahmed, M. Demiral, A. Roy, V.V. Silberschmidt, Computational study of ultrasonically-assisted turning of Ti alloys, Advanced Material Research 223 (2011) 30–36.

[21] H. Jamshidi, M.J. Nategh, Theoretical and experimental investigation of the frictional behavior of the tool–chip interface in ultrasonic-vibration assisted turning, International Journal of Machine Tools and Manufacture 65 (2013) 1-7.

[22] A.S. Adnan, S. Subbiah, Experimental investigation of transverse vibration-assisted orthogonal cutting of AL-2024, International Journal of Machine Tools and Manufacture 50 (2010) 294-302.

[23] K.M. Li, S.L. Wang, Effect of tool wear in ultrasonic vibration-assisted micro-milling, Journal of Engineering Manufacture 228 (2014) 847-855.

[24] X.H. Shen, J.H. Zhang, H. Li, J.J. Wang, X.C. Wang, Ultrasonic vibration-assisted milling of aluminum alloy, International Journal of Advanced Manufacturing Technology 63 (2012) 41-49.

[25] R. Muhammad, A. Maurotto, A., Roy, V.V. Silberschmidt, Characterization of thermomechanical loads in vibro-impact machining of advanced alloys, Applied Mechanics and Materials 70 (2011) 315-320.

[26] N. Ben Moussa, H. Sidhom, C. Braham, Numerical and experimental analysis of residual stress and plastic strain distributions in machined stainless steel, International Journal of Mechanical Sciences (2012) 82-93.

[27] G.L. Chern, Y.C. Chang, Using two-dimensional vibration cutting for micro-milling, International Journal of Machine tools and Manufacture 46 (2006) 659-666.

[28] M. Jin, M. Murakawa, Development of a practical ultrasonic vibration cutting tool system, Journal of Materials Processing Technology 113 (2001) 342-347.