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2nd CIRP 2nd CIRP Conference on Surface Integrity (CSI)

Surface-roughness improvement in ultrasonically assisted turning

Vadim V. Silberschmidt^{a*}, Sameh M. A. Mahdy^b, Moustafa A. Gouda^b, Ahmed Naseer^a,
Agostino Maurotto^a, Anish Roy^a

^aLoughborough University, Ashby Road, Loughborough, Leics., LE11 3TU, UK

^bThe British University in Egypt, El-Shorouk City, Cairo 11837, Egypt

* Corresponding author. Tel.: +44 531 227504; fax: +44 531 227502. E-mail address: V.Silberschmidt@lboro.ac.uk.

Abstract

Ultrasonically assisted machining is a hybrid technique based on superimposition of ultrasonic vibration on a movement of a cutting tool. Such vibration with relatively small amplitude – below 20 microns – changes dramatically the response of a machined material to a cutting process. As a result, a significant – in excess of 80% in turning of aerospace superalloys – reduction of average cutting forces is observed together with improvement of surface roughness. The paper presents results of analysis of the effect of ultrasonically assisted turning (UAT) on surface roughness (using a broad range of parameters) for a broad range of metals and alloys – from copper, aluminium and stainless steel to Ni- and Ti-based alloys. The effect of machining parameters for both conventional turning and UAT was investigated to provide an optimum range for each material and its relation to surface roughness.

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1. Introduction

Ultrasonically assisted machining has demonstrated its advantages over traditional machining techniques for many types of processes and materials. One of the considerably studied areas is ultrasonically assisted turning (UAT), where the ultrasonic vibration with a relatively small amplitude (some 10 microns) is superimposed on the movement of the cutting tool [1-4]. The research, undertaken at Loughborough University, UK, demonstrated several important advantages of this hybrid machining technology, including a significant force reduction and improvement of the surface finish.

These achievements were apparent even for such a hard-to-machine alloy, as Inconel 718, used for high-temperature applications [3-6]. Further research on the effect of UAT on machinability of intractable materials was linked with several Ti- and Ni-based alloys [7-9], followed by studies of several traditional structural metals and alloys [10]. In all cases, significant improvements in machinability were demonstrated.

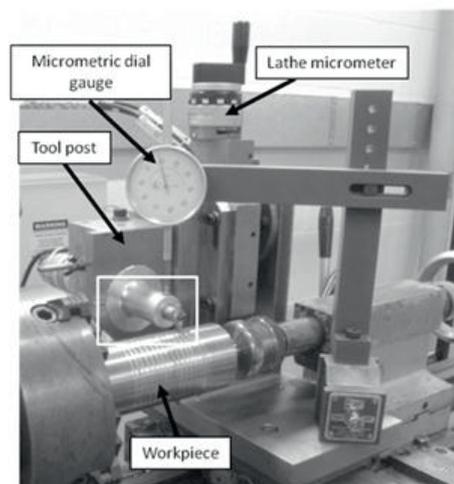


Fig. 1. Setup for ultrasonically assisted turning (white frame demonstrates sonotrode with cutting insert at its end)

They were possible thanks to a unique in-house setup (Fig. 1) for ultrasonically assisted machining that allows

achievement of force reduction in some cases in excess of 90 per cent. The setup makes possible to switch ultrasonics on and off even during the same machining run, eliminating a need to use two different systems for conventional turning (CT) and UAT and underpinning direct compatibility of the obtained results. A typical example of such comparison is given in Fig. 2 for all three cutting force components, measured with Kistler dynamometer (model Kistler 9257 A). Apparently, superimposition of ultrasonics causes an immediate drop in the level of two main components – tangential and radial – that are re-gained after the end of excitation off.

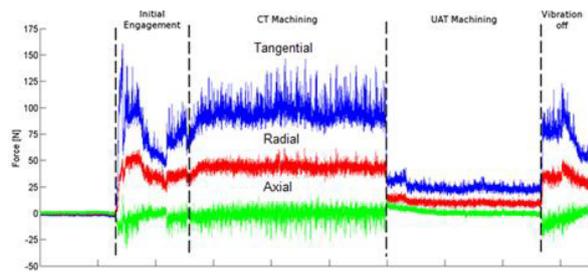


Fig. 2. Evolution of force-component signals for CT and UAT recorded with dynamometer in single run

Such a significant force reduction is accompanied by a change in mechanical behavior of the machined material in a process zone, manifested by a considerable change in the noise signature, the type of chip and reflectivity of the formed surface. All these processes should affect properties of the machined surface, including its integrity and roughness as well as residual stresses in sub-surface layers.

This study provides a first systematic analysis of the effect of ultrasonically assisted turning on surface roughness of a broad set of machined materials.

2. Materials

The main motivation of this study is to compare response of various metals and alloys – from ones with known good machinability to hard-to-machine ones. A second-generation UAT setup that provided record-breaking force reductions was used systematically in all the studies. The choice of materials was defined by several reasons. On the one hand, hard-to-machine materials, like Ni- and Ti-based alloys, were chosen because of their known manufacturing challenges that can affect their introduction into various aerospace, engine and power-energy applications.

More traditional materials, such as stainless steel, aluminium, brass, bronze and cast iron, on the other hand, used mostly not in the high-end (and expensive) components and structures, can benefit from increase material-removal rate (for the same level of cutting

forces), affecting mass-production manufacture.

The materials used in the study comparing the effect of two machining techniques – CT and UAT – on surface roughness are presented in Table 1. Some comments on them are given in respective sections below.

Table 1. Studied materials (wt.%)

Material	Notation	UAT
Inconel 718	In 718	Al:0.50/B:0.003/Bi: <0.00003/C:0.028 /Co:0.21/Cr:18.46/Cu:0.04/ Fe:18.82 /Mg:<0.001/Mn:0.05/Mo:2.98/Ni:52.8 /P:0.007/Pb:0.0002/S:0.002/Si:0.08 /Ti:0.97/Nb:4.95/Ca:0.001/Ta:0.01
Ti 15 3 3 3	Ti 15333	Ti:75.52/Al:2.59/Cr:3.43/Sn:3.07 /V:15.39
X2CrNi18-9	SS	C:0.06/Mn:0.9/Si:1/P:0.05/S:0.02 /Cr:18/Ni:8
ASTM A 48 class 20	CI	C:3.2/Mo:0.1/Cu:0.2/Mn:0.5/Si:1 /P:0.1/S:0.01/Cr:0.2/Ni:0.1
AlMg1SiCu	Al	Al:98.2/Cr:0.04/Cu:0.15/Fe:0.7 /Mg:0.9/Mn:0.1/Si:0.5/Zn:0.1
CuZn37Pb2	Br	Cu:62/Zn:37/Pb:2
CuSn11P	Bro	Cu:89/Zn:0.25/Sn:11/Pb:0.15
X2CrNi18-9	SS	C:0.06/Mn:0.9/Si:1/P:0.05/S:0.02 /Cr:18/Ni:8

3. Surface Roughness

3.1. Methodology

In order to quantify the surface improvement brought about by UAT, surface analysis studies were performed using two different techniques: Zygo® interferometry and Talysurf® technique. The former method allows an analysis of the area of interest with the latter providing high-precision data for a chosen path.

Talysurf® is a stylus-type surface texture-measuring instrument, in which the stylus is traversed across the surface and the pick-ups convert 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. 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 advantage of this type of pick-up is that it enables a true recording of waviness and forms to be obtained.

The Zygo® newview 5000 is a non-contact instrument that uses white-light interferometry to acquire topography of a measuring surface. With the software MetroPro produced by Lambda Photometrics it allows the acquisition of high-resolution 3D contour plots to characterize the surface structure of the test area. The instrument provides very accurate measurements of surface contour in a fraction of the time needed by a contact instrument.

3.2. Results for Inconel 718

Inconel 718 is a precipitation-hardenable nickel-chromium alloy containing significant amounts of iron, niobium, and molybdenum along with lesser amounts of aluminium and titanium (see Table 1). It combines good corrosion resistance and high strength with outstanding weldability, including resistance to post-weld cracking.

The results obtained from the Zygo® interferometry proved better surface results in case of UAT of Inconel 718 as compared to CT. Table 2 presents the comparison of different surface profilometry results for two methods.

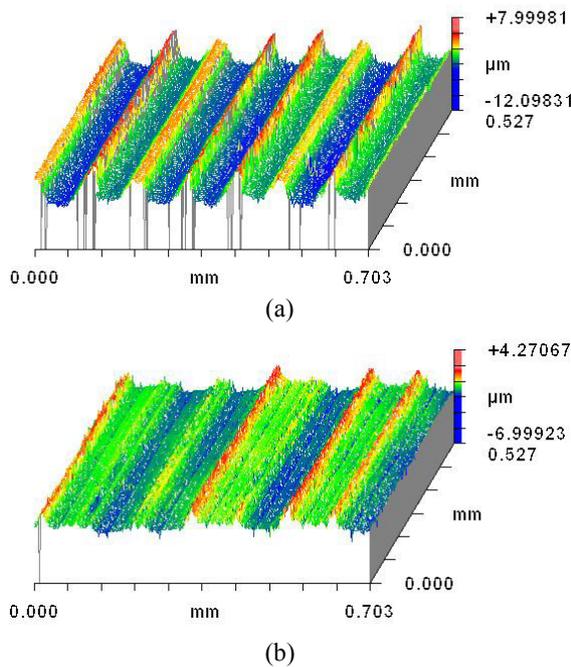


Fig. 3. Surface 3D plots for Inconel 718 in CT (a) and UAT (b)

Table 2. Results for Inconel 718

Parameters	CT	UAT
R_q [μm]	2.081	0.659
R_a [μm]	1.719	0.505

The R_a value in case of CT is 1.719 μm as compared to 0.505 μm in case of UAT. The results from Zygo® were also helpful in understanding the effect of micro-impacts in UAT on the workpiece’s surface caused by vibration. A surface profile diagram of the UAT workpiece along the direction of cut showed approx. 70 oscillations along the length of cut 0.53 mm. This is equal to the number of micro-impacts, to which the workpiece was exposed to during the respective period of UAT with a frequency of 20 kHz for a cutting speed

of 80 rev/min. Note that the average peak-to-valley height of this formed surface pattern is 0.3 μm for a vibration amplitude of approx. 13 μm . Hence, even with the non-continuous character of the tool movement during UAT, it provides a better surface finish of Inconel 718.

3.3. Results for Ti 15 3 3 3

Machining processes of titanium alloys are generally characterised by low cutting feeds and speeds ranging from 12 to 38 m/min for aged alloys [11]. This increases machining times and therefore costs, especially when a large amount of material should be removed to produce a finished component. Besides, their poor thermal conductivity results in localised high-temperature zones in areas with high friction, such as flank and rake face of the tool. High temperatures and high chemical reactivity of these alloys accelerate tool wear and ultimately cause premature tool failure [12].

Therefore, rapid tool wear, high cutting forces, poor surface finish and poor dimensional accuracy of the finished component require several finishing steps to manufacture a component with the desired quality, increasing overall costs [13]. Ultrasonically assisted machining demonstrated its capability to improve the machining characteristics of intractable alloys, with a cutting force reduction in excess of 50%, reduction of chatter and improvement of the surface quality of the finished work-piece [7, 14-16].

A detailed investigation of surface finish of Ti 15 3 3 3 workpieces, presented in Fig. 4 and Table 3, demonstrates that – thanks in part to a large reduction in cutting forces – UAT is more beneficial in this regard. In terms of R_a , for instance, the UAT-generated surface of the machined workpiece has a nearly twofold improvement, with R_q demonstrating nearly the same (somewhat smaller) effect. But the extent of improvement for this Ti-based superalloy was still less than that achieved for Inconel 718.

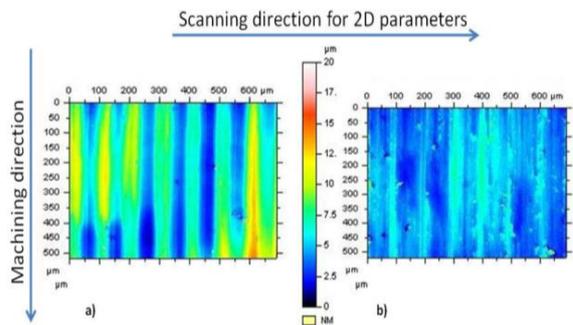


Fig. 4. Surface plots for Ti 15 3 3 3 for $a_p=0.2$ mm in CT (a) and UAT (b), $V=10$ m/min, $f=0.1$ mm/rev

Table 3. Surface topography parameters for Ti 15 3 3 3 for two turning techniques

Parameter	CT	UAT
Arithmetic mean deviation R_a [μm]	1.73 ± 0.33	0.89 ± 0.25
Root-mean-square R_q [μm]	1.98 ± 0.33	1.17 ± 0.35
Skewness R_{sk}	0.11 ± 0.24	0.73 ± 0.54
Kurtosis R_{ku}	1.94 ± 0.48	3.92 ± 1.58
Mean width of the profile elements P_{sm} [μm]	104.9 ± 18.1	53.8 ± 22.7
Arithmetic mean of the absolute height S_a [μm]	2.14 ± 0.27	1.21 ± 0.28
Root-mean-square of the height S_q [μm]	2.58 ± 0.36	1.56 ± 0.34
Density of peaks S_{pd} [mm^{-2}]	140 ± 53	764 ± 335
Arithmetic mean of principal curvatures S_{pc} [mm^{-1}]	1.05 ± 0.26	1.82 ± 2.64

3.4. Results for structural metals and alloys

After demonstrating of significant improvements in application of ultrasonically assisted turning to hard-to-machine alloys, it was decided to extend a research into UAT to more traditional metals and alloys. Materials chosen to investigate represent a wide range of industry day-to-day used materials. Those include: stainless steel (SS), brass (Br), bronze (Bro), aluminium alloy (Al) and cast iron alloy (see Table 1). The five studied categories of specimens represent two ferrous alloys with different carbon content and three nonferrous alloys.

Additionally, as cutting forces change with an increase in the cutting speed (v), they can affect surface roughness. This effect has also been investigated for a range of other machining parameters such as depth of cut (a) and feed rate (f). The main results of these studies are presented in Figs. 5-7.

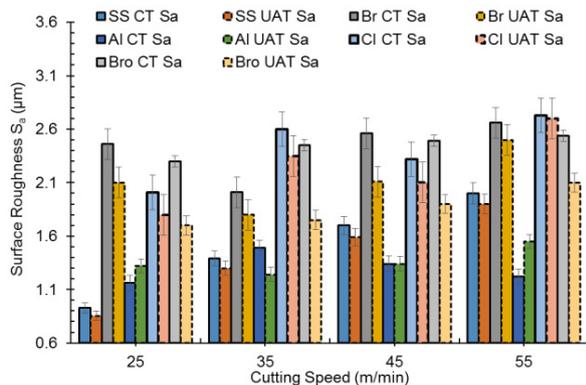


Fig. 5. Effect of cutting speed on surface roughness average for five different materials under both CT and UAT ($f = 0.2 \text{ mm/rev}$, $a = 0.3 \text{ mm}$; vibration frequency 20 kHz, amplitude $8 \mu\text{m}$)

Apparently, for harder materials – bronze and stainless steel – larger values of roughness were found as the cutting force increased due to larger hardness. All the values for UAT are lower than those for CT because,

affected by the reduced cutting forces and the intermitted contact conditions [9]. As feed increased, higher cutting forces were induced resulting in roughness increases; still, UAT cutting forces were lower so surface roughness in case of UAT was less than in CT.

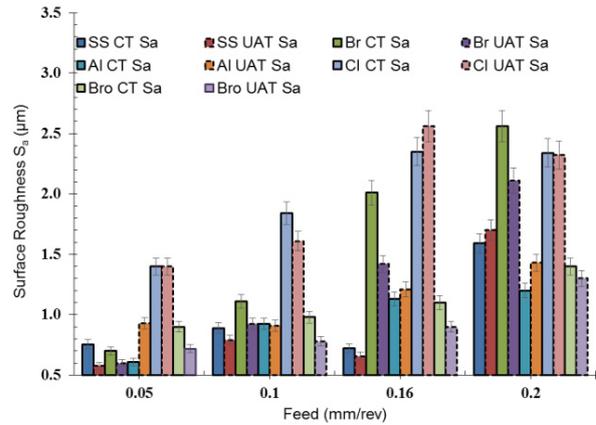


Fig. 6. Effect of feed rate on surface roughness average for five different materials under both CT and UAT ($v = 35 \text{ m/min}$, $a = 0.3 \text{ mm}$; vibration frequency 20 kHz, amplitude $8 \mu\text{m}$)

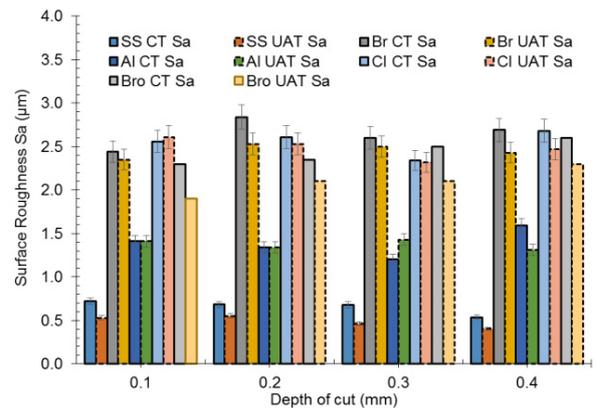


Fig. 7. Effect of depth of cut on surface roughness average for five different materials under both CT and UAT (vibration frequency 20 kHz, amplitude $8 \mu\text{m}$)

4. Surface integrity

Apart from the character of the surface topography introduced by a machining process, its effect on sub-surface layers is of importance. Surface integrity (when machining is used as a finishing process) significantly affects performance and durability of the components. For instance, surface defects can decrease fatigue loads and life-in-service, while tensile residual stresses can accelerate crack propagation.

One possibility to study these manufacturing-induced factors, micro-indentation can be employed together with microstructural analysis of subsurface layers (here,

the study is limited only to Ti 15 3 3 3).

To implement micro-indentation tests, the workpiece was sectioned using an automated metal saw, at low cutting speed and feed, and with pressure-fed coolant and lubricant. It was then sliced into small pieces, which could be directly loaded into the used testing system, NanoTest NTX3 from Micro Materials. The samples were glued with cyanoacrylic adhesive to a sample holder, which was fixed with screws to the system's slide. Areas of measurements on the machined surface were selected far from the cut edges in order not to introduce errors; NanoTest NTX3 allowed performing fully automated tests on several areas of surface.

Each indentation test consisted of several indentation points close to each other; the pattern used was a parallelogram shaped cluster of 9 measurements arranged in 3 columns spaced 200 μm and staggered by 100 μm . This pattern was employed to lower the chance of obtaining single-grain indentations since Ti 15-3-3-3 had large grains ($\geq 100 \mu\text{m}$). A standard, diamond-tip Vickers indenter was used for all the tests.

The tests were performed with a fixed maximum load of 2 N, achieving penetration of the indenter below 7 μm . This shallow depth was chosen for two reasons: it allowed to use the machine well below its maximum load of 20 N and limited the investigation to the immediate surface, which was considered of interest in this study.

Before performing indentations on the machined surface, one sample away from the machined surface was prepared by careful wet-grinding, in order to avoid introducing any changes. This specimen (denoted as *bulk*) was used to assess bulk properties of the alloy as a reference for the values obtained for the machined surface. The measured hardness of this specimen was similar to that provided by the manufacturer, confirming that the technique used for measurements was adequate.

Since higher depths of cut generate higher cutting forces and generate higher temperatures in the process zone, it was expected that specimens with the higher cutting depth would show larger deviations from the reference bulk properties.

Analysing the obtained results, it was observed that surfaces machined with CT and UAT behaved very differently (Fig. 8). Surface hardness of the CT-machined workpieces appeared to be higher than hardness of the bulk, i.e. unprocessed, material. The maximum effect was observed for the depth of cut (DoC) of 0.2 mm. This effect was however not replicated in the UAT tests (Fig. 8). Based on the surface-indentation tests it was concluded that surface hardness in UAT differed very little from the bulk one. This interesting finding was not expected since the strain rate, to which the material was subjected during UAT, was higher than in CT. Therefore, a higher surface

hardness in UAT surfaces was to be expected if strain-hardening should be the main (or only) factor affecting hardness. Other causes could be metallurgical (grain or phase changes) or residual stresses.

To rule out possible effects of surface roughness on hardness, deeper indentation was performed on the sample cut with depth of cut of 0.5 mm, reaching a depth of approximately 15 μm with a force of 10 N (the same Vickers micro-indenter was used). The sample was chosen since the high DoC would enhance the thermal and deformation effects. The results once more demonstrated the level of hardness for UAT being 12% lower than that for CT.

These studies should be continued since the current indentation depth is still comparable with the peak-to-valley height; hence, surface roughness can affect the results of these measurements. Another factor is an effect of a surface white layer and a heat-affected zone (see [20] for details). Both zones usually contribute to increased hardening, and our observations that UAT results in hardness are close to those of as-delivered materials are potentially the result of lower invasiveness of UAT.

The fact that ultrasonically machined surfaces show hardness comparable to those of the virgin material could be beneficial to the industry since the bulk hardness of the material is preserved. The investigation however did not completely rule out the effect of microstructural changes in the material. Thus, a direct observation of the material surface was performed.

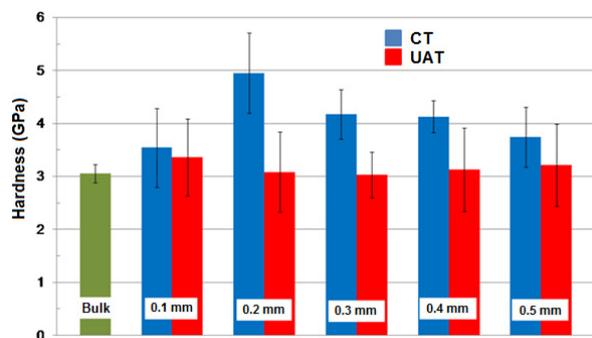


Fig. 8. Surface hardness for CT and UAT machined surfaces of Ti 15 3 3 3 at different depths of cut, $v = 10 \text{ m/min}$, $f = 0.1 \text{ mm/rev}$

The optical metallographic analysis (Fig. 9) did not demonstrate presence of any grain structure different from that observed in the bulk, non-machined state of this alloy. This result, when associated with the absence of significant hardness changes could rule out the possibility of α -casing formation in the ultrasonic machining of Ti 15-3-3-3. It was possible to notice that a thin layer (5-10 μm) with a different shine in optical-

microscopy results appeared just under the machined surface. The EBSD analysis excluded the presence of α -Ti in this sub-surface layer; therefore, it was deemed necessary to investigate it in more detail. SEM demonstrated that layers generated by both studied turning techniques – CT and UAT – have the same thickness of approximately 5 μm , i.e. smaller than the maximum indentation depth. This type of layer has the feature of a strongly deformed area; apparently, its influence on hardness is small and both techniques did not differ in this respect.

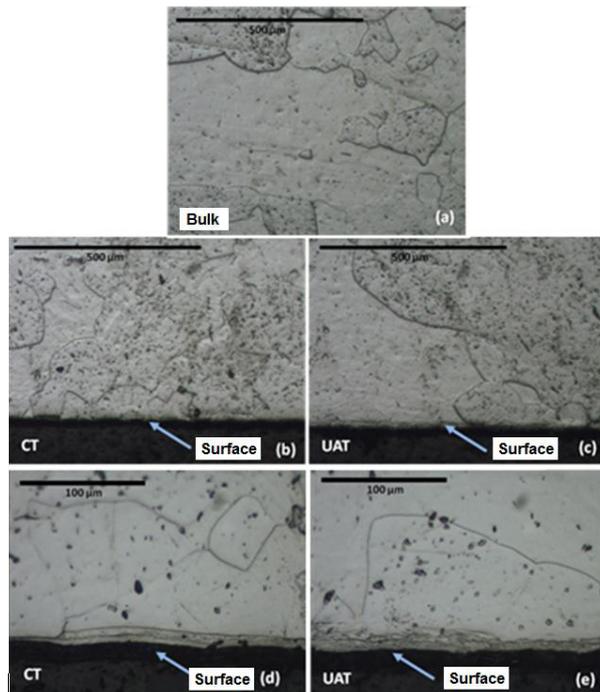


Fig. 9. Etched cross sections of work-pieces of Ti 15 3 3 3: (a) virgin-state bulk sample; (b, d) machined with CT; (c, e) machined with UAT. Note different scales

Conclusions

The hybrid turning technique UAT – resulted in noticeable improvements in surface roughness of all the studied alloys, with its inherent decrease in cutting forces being the main reason for this. This was observed for all the combinations of cutting parameters used, and in all the materials; obviously, the extent of the improvement differed.

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