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Design and development of an ultrasonic vibration assisted turning system for machining bioabsorbable magnesium alloys

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Abstract

Magnesium alloys are emerging as potential candidates for degradable temporary implants thanks to their mechanical properties that are closer to those of the natural bone compared to other metals, their good biocompatibility, non-toxicity and biodegradability. However, once placed in the human body, they tend to corrode too quickly, loosening their structural stability before the end of the period of complete healing. Different techniques have been applied to magnesium alloys in order to improve their surface integrity, which is directly correlated with the corrosion resistance. In this study, an Ultrasonic Vibration Turning (UVT) system was applied to machine a biodegradable magnesium alloy. The vibrating tool was preliminary designed with Finite Element (FE) software aid, in order to identify a first model of sonotrode shape, to match the resonance frequency of a commercial transducer. Consequently, a procedure for the system fine tuning was carried out, involving the indirect measure of the system impedance. Finally, different process parameters, namely cutting speed and depth of cut, were used in order to machine the magnesium alloy, obtaining different surface textures. The obtained results suggest that the ultrasonic vibration turning can be efficiently applied to machine biodegradable magnesium-based materials for biomedical applications.

Keywords: ultrasonic machining; surface texture; magnesium alloy.

1. Introduction

Recently, Ultrasonic Vibration Turning (UVT) successfully demonstrated its advantages in machining tough and brittle materials [1]. UVT, with its peculiar high frequency alternative motion given to the cutting tool, limits cutting tool wear when machining difficult-to-cut materials, such as superalloys, ceramics and glass, resulting effective in ultra-precision turning of components of tight geometric tolerances. Moreover, the cutting tip oscillating motion lowers the cutting forces and increases the heat removal.

At the same time, UVT induces on the workpiece surface a distinctive structured textured that could improve mechanical, biological and optical properties [2]. It is well known that surface textures play an important role to determine the product in-service performances [3]: as example, distinct geometric patterns can avoid debris presence between two sliding surfaces or retain a secondary source of lubricant improving wear resistance.

Several authors, in order to operate UVT, developed one dimensional and two dimensional vibrating cutting tools [4]. The first, the so-called resonant 1-D system, is driven by an ultrasonic transducer, and the tool tip, located at the other end of a sonotrode, withstands a harmonic motion with high frequency and low amplitude. The motion can follow the cut direction axis or the radial one. Characteristic frequencies are within 20-40 kHz and typical amplitudes are between 2 and 100 μm. Other researches focused on the development of a 2D

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vibrational system known as Elliptical Vibration Assisted Turning (EVAT) [5], which was realized arranging two piezoelectric transducers of a proper geometry preliminarily designed on the basis of finite element modelling. The amplitude of vibration in the two axes may not be the same and can be adjusted varying the phase shift of the two piezoelectric transducers driving signals.

In this work, ultrasonic motion is applied to a turning tool in order to create structured textured on a magnesium alloy of biomedical interest. Magnesium alloys are nowadays attracting more and more attention for biomedical applications thanks to their biodegradable nature, low density and elastic modulus comparable to that of the natural bones. However, to be used for biodegradable implants, their corrosion resistance to human body fluids needs to be improved. Severe Plastic Deformation (SPD) processes, such as Equal Channel Angular Pressing (ECAP), have proved to enhance their corrosion behaviour by improving their surface integrity in terms of sub-surface microstructural and mechanical features. In this context, the action of an ultrasonic tool [6] can be beneficial to create a surface pattern less prone to be attacked by body fluids yet not compromising the alloy biocompatibility.

The paper is divided into three parts: the first one is devoted to the description of the design and implementation of the UVT method for the generation of textured surfaces with a one-dimensional oscillating cutting tool, the second part reports the description of the experimental campaign, and, finally, the third part shows the analysis of the obtained texture pattern on the basis of surface topography measurements and Scanning Electron Microscope (SEM) analysis.

2. Design of equipment

The current UVT system was designed making use of a piezoelectric transducer, a sonotrode, a tool tip, a mechanical setup to fit in the turret of the Mori-Seiki NL-1500 CNC™ lathe, and driving electronics. The transducer is a bolt clamped Langevin type [7]: two piezoelectric rings are preloaded under the action of an aluminium truncated cone shape and a cylindrical steel head.

Particular attention was paid to the sonotrode shape design as its performance directly affects the amplitude of the cutting tool. The overall length of the sonotrode, known as ultrasonic horn, is, as first approximation, independent from its shape, and is the only parameter that identifies the natural resonance frequency, besides the speed of sound in the material. On the other hand, the natural resonance frequency has to match the bare transducer resonance frequency within a narrow tolerance, in the order of half a kHz. In order to pursue this goal, an iterative measuring-adjustment experimental method was adopted, after a preliminary analytic modelling of the sonotrode behavior [8].

The cutting tool was firmly fixed to an aluminum tip offering a threaded hole to fit the sonotrode.

The scheme of the UVT system with indication of the different parts is shown in Figure 1.

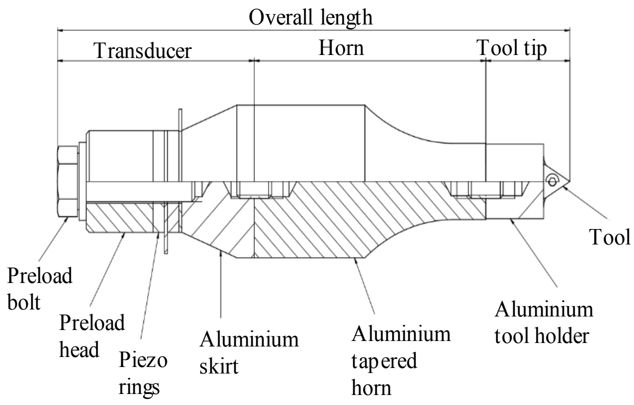

Figure 1. Sketch of the UVT system.

The FEM code NASTRAN® was used to evaluate the vibration behavior of the horn and overall UVT system before being manufactured. The minimum impedance method was used to check the horn resonance and match the transducer one.

The applied procedure consisted in monitoring the current crossing a reference 100 Ohm resistance in series with the piezoelectric transducer with the 2 channel digital oscilloscope Tektronix TBS1052B™: the monitored frequency-dependent current was variable and the power was supplied by a signal generator (Siglenet SDG800™) set up to feed a sine sweep of 4 Vpp constant amplitude starting at 20 kHz and ending at 40 kHz for a total duration of 100 microseconds. The current trend was registered through the oscilloscope and the resulting plot showed sharp peaks and troughs representing the minimum and maximum impedance frequencies, respectively.

The overall length of the sonotrode had to be shortened until the minimum impedance point was located in correspondence of the natural resonance frequency of the transducer previously measured with this method.

This method helped in identifying in a few steps the right horn length but did not provide any useful information about the impedance real value. The impedance value of the transducer-horn-cutting tip system versus the frequency spectra is indeed a fundamental data set to design the ultrasonic piezoelectric driver. In order to estimate the impedance value of the sonotrode-piezotransducer assembly, the voltage magnitude and the phase shift between the 2 channels of the oscilloscope were measured: the first channel of the scope monitored the voltage drop of the transducer-sonotrode assembly with a 100 Ohm resistance in series, while the transducer poles were just wired to the second channel. The signal generator (Siglenet SDG800) was operated to feed a sine signal by manually varying its period around the minimum impedance frequency, which was previously located: in such a way, it was possible to draw the impedance versus frequency graph and reveal its minimum of 86 Ohm at 30 kHz.

Figure 2 shows the workflow for the overall design of the UVT system.

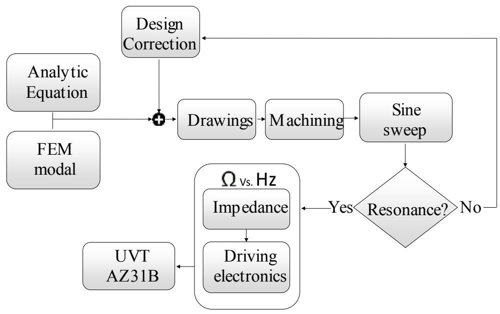

Figure 2. Workflow of the design procedure.

3. Experiments

The material under investigation was the commercial AZ31B magnesium alloy, which frequency

was supplied in form of bars of 30 mm of diameter.

The machining tests were conducted on a Mori Seiki™ NL-1500 CNC turning center equipped with a customized steel structure for holding the developed UVT system. This structure was designed to allow a fine height adjustment of the tool cutting edge in the lathe Y-axis (center-line) housing in a standard 20 mm tool shank slot. Referring to the lathe coordinate system, the alignment of the sonotrode axis in the X direction was obtained with a precision set-square. Before ultrasonic turning, the magnesium alloy bar was prepared with a Conventional Turning (CT) finishing pass with the same UVT system where ultrasonic vibration was turned off in order to guarantee the nominal value of imposed depth of cut. Figure 3 shows the direction of motion of the UVT system during cutting.

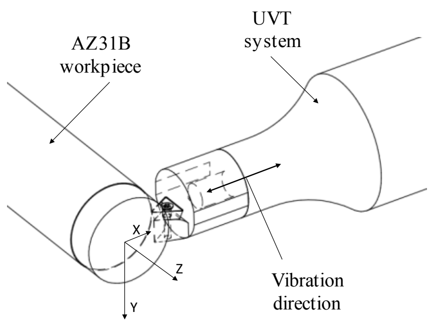

Figure 3. UVT vibration axis along X axis, feed along Z axis.

Table 1 summarizes the cutting parameters applied in the experimental campaign in terms of cutting speed (*Vc*), Depth Of Cut (*DOC*) and feed (*f*).

Table 1. Cutting parameters for the experimental campaign.

	Turning	DOC (mm)	Vc (m/min)	f (mm/rev)
# 0	CT	0.05	100	0.05
# 1	UVT	0.05	100	0.05
# 2	UVT	0.05	200	0.05
# 3	UVT	0.1	100	0.05
# 4	UVT	0.1	200	0.05

The surface topography of the machined samples was measured using a Sensofar Plu Neox™ surface profiler with a 20x magnification Nikon™ confocal objective. Each reported value is the average of nine different measurements. Different areal surface texture parameters were considered, namely Sa, Spk, Svk, Ssk and Sk.

The mapping of the machined surface defects was performed using a FEI™ QUANTA 450 SEM. The machined surface was inspected in different areas to assure a comprehensive analysis.

4. Results

The surface topography of two samples machined using the UVT system at 100 m/min and 200 m/min, respectively, with DOC equal to 0.1 mm, is shown in Figure 4. The final amplitude and frequency of vibration was 20 µm and 30 kHz, respectively. It is worth to note that the designed topography in terms of distance between two subsequent gaps was readily obtained. This distance can be expressed through Eq. (1):

$$d_{gap} = \frac{V_c}{60f} \tag{1}$$

where d_{gap} is expressed in mm, Vc is the cutting speed in m/min, and f is the frequency of vibration in Hz.

The texture obtained on the surface is regular and the pattern is repeated periodically (see Figure 4) confirming the direct proportionality between dimples distance and cutting speed, and, therefore, proving that the UVT system works within its design limits, vibrating the tool along a space-fixed axis with sufficient stiffness.

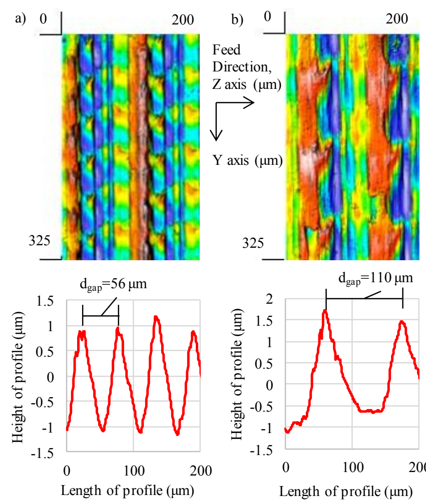

Figure 4. Topography and profile along the Y axis of two samples machined at: a) 100 m/min, DOC 0.1 mm, and b) 200 m/min, DOC 0.1 mm using the UVT system.

Figure 5 reports the comparison between surface area parameters obtained after CT and UVT. The obtained results show that UVT strictly influences the morphology of the profile by changing the material distribution, as demonstrated by the increase of all the reported surface texture parameters. Rougher surfaces are obtained using UVT, with an increase of 85% compared to CT. Also functional parameters, like Svk and Spk, resulted in a drastic increase. This indicates that UVT distributes more material on the roughness peaks and contributes to increase the depth of the valleys. Height parameters, like Sku and Ssk, raise to approximately 41% and 140% compared to CT, meaning that an increased number of spikier peaks protrude above the mean line. These findings are confirmed by the partial profiles of the surfaces measured after machining reported in Figure 5b.

Figure 5c shows the effects of machining parameters adopted during UVT on the surface texture parameters. A trend cannot be identified for any of the investigated parameters, even if it is evident that both the cutting speed and DOC influence these parameters to a significant extent.

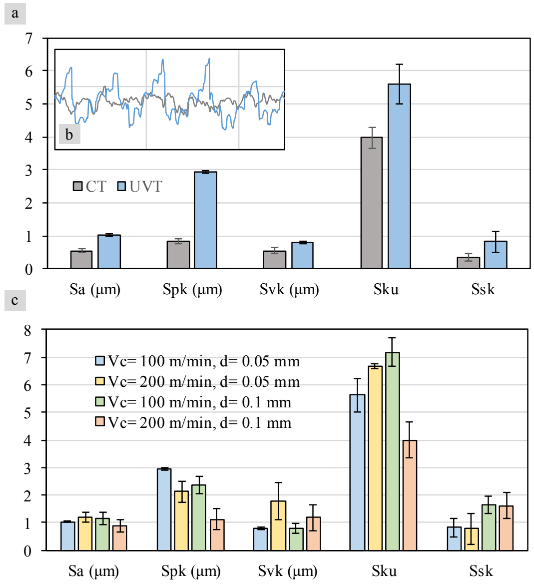

Figure 5. a) Surface texture parameters of CT and UVT; b) 2D profiles; c) surface texture parameters as a function of the cutting parameters in case of UVT.

It is well known that surface topography plays an important role in determining functional performances of the machined products, such as wettability. Since the latter is a measure of the interaction between the material and the environment, it has been recently identified that its increase can represent a potential strategy to improve corrosion resistance of magnesium alloys [9]. To this regard, the surface profile induced by UVT is potentially positive to reduce wettability as it is characterized by a higher number of peaks than CT, which can increase the area fraction of the solid–liquid contact supporting the liquid droplets, therefore inducing more hydrophobic surfaces.

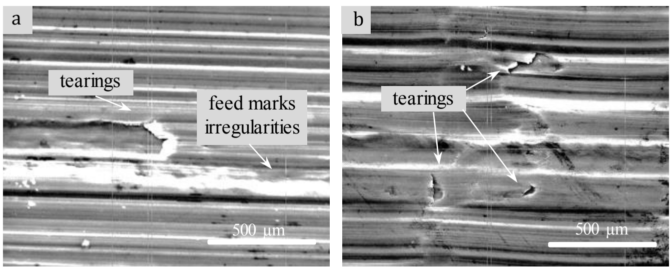

Figure 6. Examples of surface defects found after: a) CT and b) UVT.

Figure 6 shows the main defects found on the surface of the samples machined using CT and UVT. SEM analysis of the machined surfaces is essential to identify defects that are not possible to detect by the surface roughness measurements, therefore providing an evaluation of the machined surface nano-texture. Tearing and feed marks irregularities represent the only defect-type found in the samples machined using both CT and UVT. Tearing can develop from the action of debris of the cutting tool, formed as a consequence of tool wear, together with fragments of Built-Up Edge (BUE), which slide on the newly machined surface giving rise to a three-body wear mechanism. Since wear debris and BUE fragments are harder than the workpiece material, they scratch and tear away the machined surface. Deformation of feed marks occurs as a result of the material plastic flow during cutting. As tearing appears on the surface of samples machined using conventional and ultrasonic approach, it can be stated that this type of defect is not generated by the tool vibration.

5. Conclusions

In this paper an UVT system was designed to modify the surface texture of the AZ31 magnesium alloy in order to increase its corrosion resistance in human-like environment. The following conclusions can be drawn:

- The UVT system demonstrated the expected functionality on the basis of the design requirements: the machined surface topography showed a regular pattern reflecting the proper stiffness of the tool and process parameter-independent tool tip trajectory.
- The obtained surface texturing was periodical and the distance between two subsequent dimples could be controlled by varying the vibration frequency, feed and cutting speed.

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