# OBJECT SHAPING OF POLYSTYRENE WITH A SONOTRODE

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## Abstract

Rapid Prototyping methods are often based on additive manufacturing strategies. Depending on the application, it can also be considered the use of a removal manufacturing rapid prototyping methodology. In this paper the authors investigate the possibility of using the ultrasound technology for the shaping of materials that can be considered as a final object, or as a rapid manufactured mold for the creation of prototypes. In this case, free-form objects can be manufactured starting from foam like materials, and model the foam through the use of a ultrasonic horn thus shaping the desired features. The authors tested the possibility of implementing the technology onto automated systems, allowing considering the use of this system on automated manufacturing lines. Geometrical deviations from the 3D model are measured and material morphology before and after machining is analyzed.

## 1. Introduction

The initial intent of this study is to operate some traditional machining operation, like lathe-shaping and milling on samples made of polystyrene, using a sonotrode instead of a traditional tool. The authors had already tested the possibility of using a sonotrode for the shaping of foam-like materials with encouraging results [1, 2].

Industrially, some operations can be performed on polystyrene blocks using traditional machining operations. If compared to ultrasound machining, many chips are created when using cutting tools to shape the material with traditional machining operations. In addition, some Rapid Prototyping techniques (e.g. Solid Ground Curing) are a combination of additive and subtractive material operations. The shaping operation described in this work, originally intended as an innovative manufacturing process, can also be considered for integration into more complex additive manufacturing processes.

Ultrasound technology has been widely exploited in several fields in the last decades. Recently (in the last 20 years) ultrasonic blades found many applications in food industry [3]. Ultrasonic assisted food cutting offers good performance in precision, uniformity and hygiene, and is the perfect cutting technology for a wide range of industries. Other ultrasonic instruments relate to the cleaning systems, and the interest of industry in this field is clear from the high number of patents relating to both industrial devices and appliances for private use [4].

From the initial results of an ongoing research activity at the University of Pisa about the uses of ultrasound technologies in manufacturing process, it appears that ultrasounds are becoming always more and more exploited also in the biomedical field. For instance, there are many patents regarding the use of ultrasounds for the creation of holes in porous tissues [5, 6], for energizing foams that can be used for pain relief [7], or even for the manufacturing of biomedical devices like garments [8].

Focusing on manufacturing technology, ultrasounds are commonly used with hard slurries in the so called ultrasonic impact grinding, both in the macro and micro machining fields [9]. The process consists in a vibrating tool oscillating at ultrasonic frequencies used to compress abrasive slurry between the workpiece and the tool, thus inducing small cracks on the workpiece and removing the material from the workpiece itself. Mechanical action is the main working principle, even if the slurry has some thermal functions. This machining process suits perfectly for hard and brittle materials, such as glass, titanium, sapphire, ruby, diamond and ceramics [10].

Ultrasonic probes are also used for welding plastics. Nowadays, this technology cannot be considered innovative any more, since there are many papers dating back in the 70s, e.g. the excellent review of industrial application conducted by Shoh [11]. Usually a high frequency (from 15 kHz to 40 kHz) and low amplitude vibration is used to create heat by way of friction between the materials to be joined. The interface of the two parts is specially designed to concentrate the energy for the maximum weld strength.

Other uses of sonotrode in manufacturing operations are in investment casting, where solidified parts are broken from the sprue thanks to ultrasonic vibrations [12]. Furthermore the possibility of using ultrasound technology with foam-like materials has already been explored both from academics [1, 2] and from industry [13, 14].

The paper analyses the possibility of using a sonotrode as shaping tool for milling and lathe-shaping operations, evaluating the differences between theoretical shapes and real surfaces. In addition to this first analysis, the presence of debris will be evaluated, and the structural composition of the machined material will be analyzed. The accuracy of shapes created with ultrasound shaping is important to recognize the benchmark the technology aims at, evaluating its suitability in one field of application more than another one.

The work is organized as follows: Section 2 presents the methodology adopted for testing the system, while results are analyzed in Section 3. Conclusions and future works are then summarized in Section 4.

## 2. Methodology

The previous works of the authors [1, 2] analyze the use of a sonotrode for drilling operation, while the present paper aims at combining also lateral motion. An axial translation is required for the drilling operation (Figure 1a), while there are two more possibilities for shaping materials with the ultrasound technology: the first one is represented in Figure 1b, and consists of a longitudinal translation of the sonotrode, and it can be assimilated to a traditional milling operation. Figure 1c shows a combination of both axial and longitudinal translation, that is an operation common in the facing operation on the lathe.

The paper explores the possibility of implementing the work procedures represented in Figure 1b and Figure 1c mounting the sonotrode on a milling machine and on a lathe. The sonotrode has been fixed on traditional machines available at the workshop of the Department of Civil and Industrial Engineering at the University of Pisa, and on a robot made available from Gruppo Scienzia Machinale.

The aim of this study is to validate the possibility of using the ultrasound technology for shaping operations of foam like materials, and specifically of polystyrene blocks. Other materials have been considered for shaping, but experiments are still ongoing at the present moment.

Two different setups have been created for testing the sonotrode both in milling and in turning operations. Different interfaces have been created to mount the sonotrode both on the lathe and on the robot. One more setup aimed at showing the differences between a traditional milling operation and the ultrasound milling in terms of quantity of chips created.

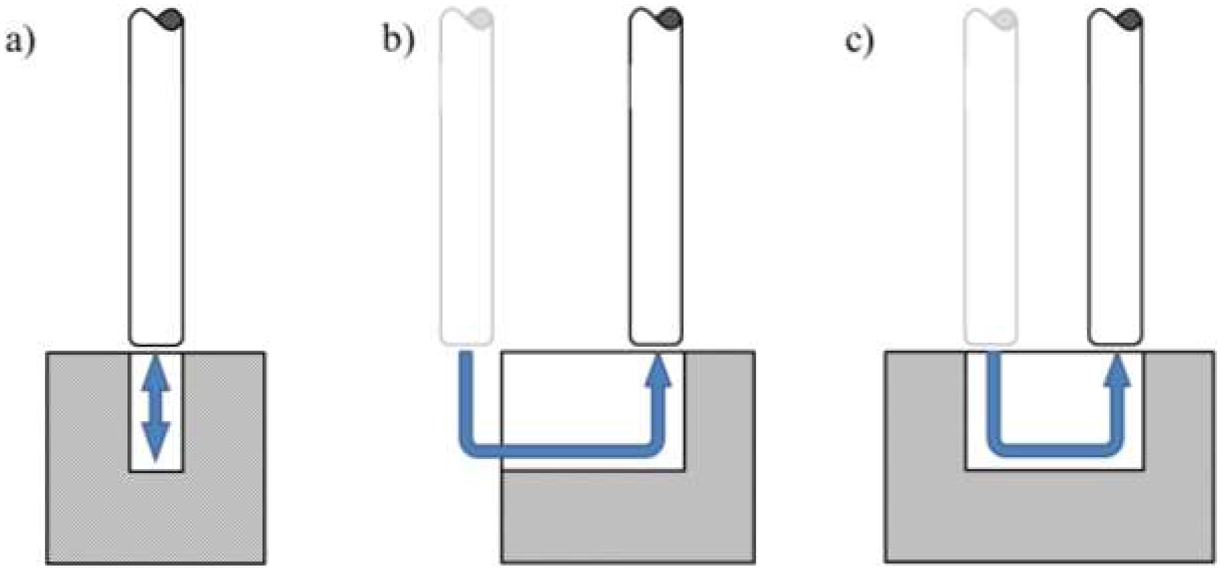


**Figure 1.** The three operations that can be performed with the sonotrode: axial removal operation (a), the longitudinal removal translation (b) and their combination (c).

The sonotrode is the core of the ultrasound machining operation. The system used for experiments is the Vibra Cell VCX 130 PB from Sonics & Materials, Inc.. The data sheet reports that the vibration frequency is constant (20 kHz), while the amplitude can be adjusted. The probe mounted on the sonotrode is an exponential one made of Titanium alloy, having a tip with a diameter of 6 mm. The sonotrode has been used at the maximum value of its amplitude for all the tests.

The working principle of the machining operation comprises both mechanical and thermal effects. The thermal effect is evident also from the presence of a small amount of chips generated: Figure 3 explains how material is deformed and where the machined material goes. The portion of material painted in blue (Figure 3a) is the part that is undergoing the deformation process. When machined with the sonotrode, Polystyrene softens and the blue volume of Figure 3a is spread on the lateral surfaces of the machined hole or groove, as shown in Figure 3b. Not all the deformed material is spread inside the groove, so some chips and debris are generated. However, the quantity of chips generated by the sonotrode is considerably lower than the one generated by a traditional tool (see Figure 2).

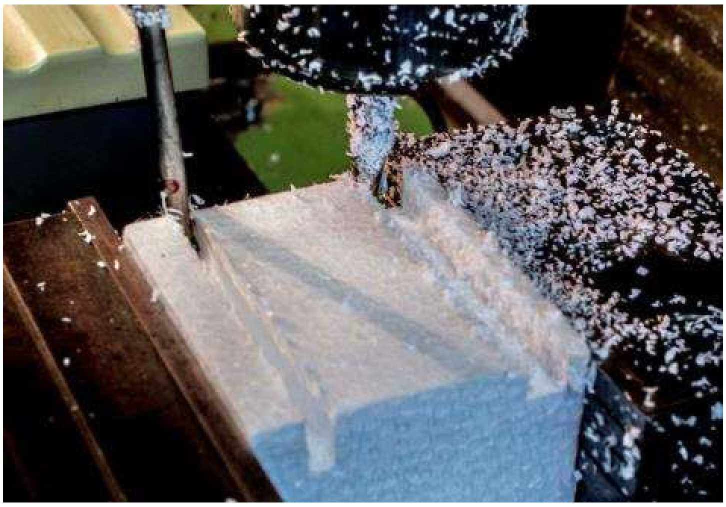

**Figure 2.** Comparison between the milling operation with the sonotrode (left) and with a traditional cutter (right).

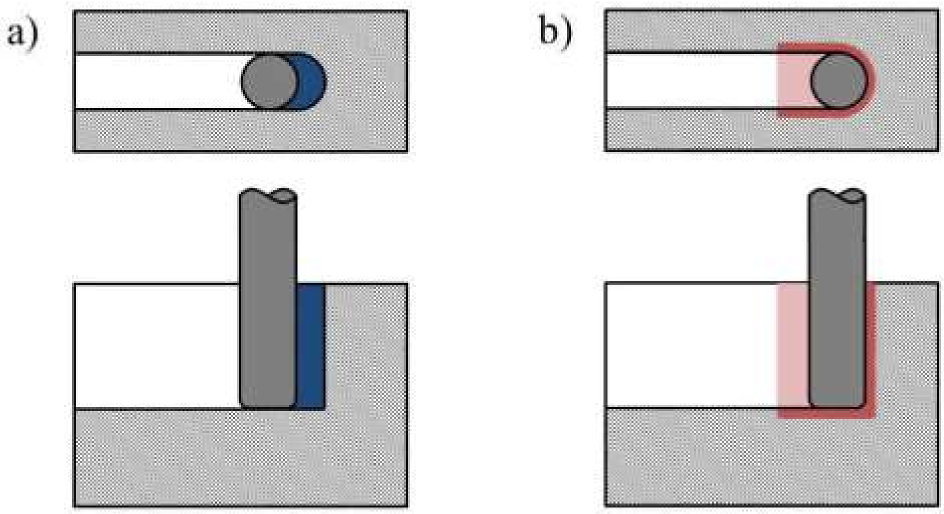


**Figure 3.** The picture shows the material that is undergoing to the deformation process (a) and the same material after the machining process (b).

### 3.1. Milling

The sonotrode was mounted on 6-axis ABB robot. The robot has been controlled in speed along the trajectories calculated with the specific software ARPP®, with a set of speeds from 5 mm/s to 20 mm/s. The software is used for the calculation of trajectories for machining operations using conventional manufacturing tools. This consideration is not trivial, since the shaping trajectory has a significant influence on the working principle of the ultrasound technology. When used as a drilling instrument, the sonotrode uses both the mechanical and thermal effect, while for the milling operations heat becomes more important. During the machining operations, the probe of the sonotrode reached 52°C, which is a significantly higher temperature if compared with the maximum one measured during the simple drilling operation (41°C).

A pyramid has been created as benchmark test for the milling operation on a polystyrene block. The initial block is approximately a parallelepiped having a square-shaped base, each side sizing 70 mm, and height 50 mm. The levels are alternatively circles and square shapes. The desired final surface is shown in Figure 4a, while the real object obtained is shown in Figure 4b. As mentioned above, some surfaces have a coarse precision due to the trajectories assigned by the software. Moreover it is evident how the surface quality is also affected by the working parameters, especially by the feed ratio. More detailed analysis on the surface will be discussed in Section 3.

One more shaping experiment was conducted on Polyurethane samples, but because of the material properties and of the high temperatures generated during the machining process, the result was not considered positive (Figure 5). As explained in [1], when machined in-air, the friction between the sonotrode and the workpiece generates a heat. While for drilling operations the process lasts few seconds, in the shaping of materials it can last long. In Polyurethane machining temperatures rose to 120°C, and heat became the only working principle, with Polyurethane becoming soft and deforming itself also without being in touch with the sonotrode (the softening point of Polyurethane varies significantly depending on the specific type of Polyurethane used). At the present moment there are ongoing experiments on different types of Polyurethane, especially on the Polyurethane known as Blue Foam, that is widely used in design modeling and in augmented reality [15].

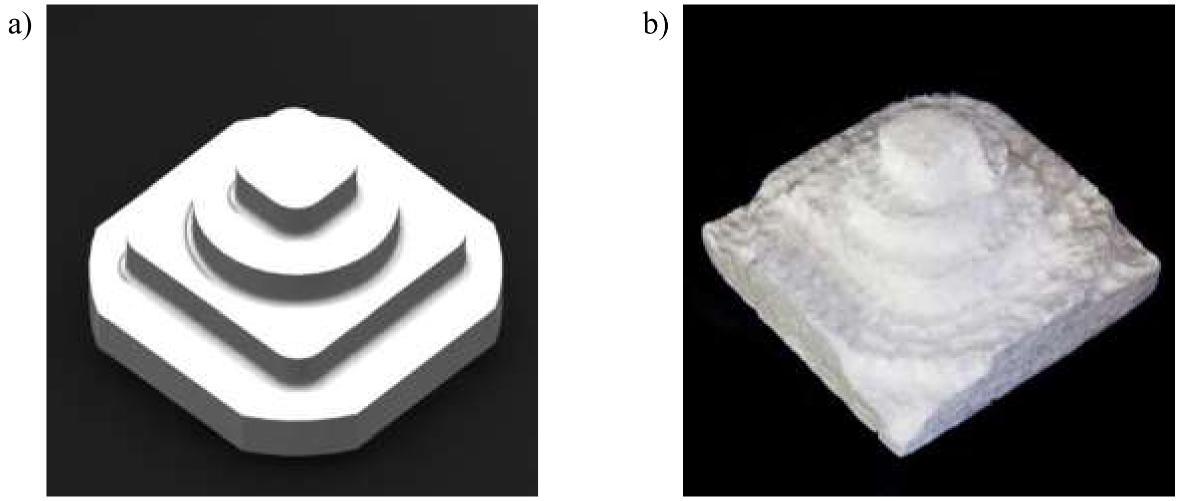


**Figure 4.** Difference between the CAD theoretical design (a) and the object shaped with the ultrasound technology (b).

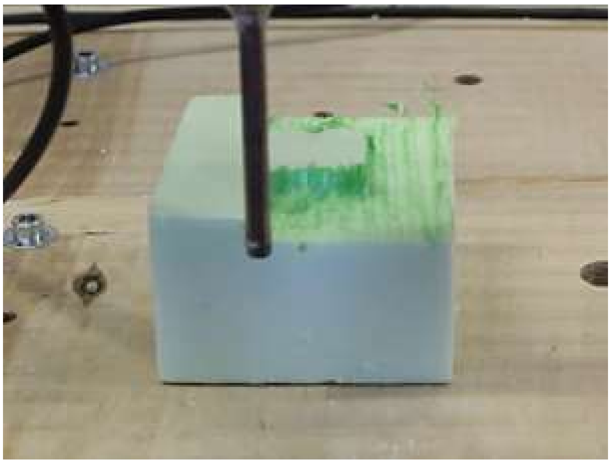

**Figure 5.** The milling operation performed on Polyurethane.

## 3.2. Turning

In order to accomplish the turning machining operation, the sonotrode was fastened to the turret-head of the lathe. The workpiece, shaped as a prism with a constant square section of 70 mm and a height of 50 mm, was fixed to the turning machine through a combination chuck. The scheme of the setup is illustrated in Figure 6. Because of the geometry of the sonotrode and the limited excursion range of the turret head in the z-axel, only face grooving operations were possible.

The shapes created in the face grooving operation on Polystyrene were circles, cylinders and spirals (Figure 7). The shapes created on Polyurethane samples were cylinders and spirals (Figure 8). The goal of the test was to evaluate the possibility of shaping material with this type of operation. The samples created on Polystyrene have been dimensionally analyzed, in order to understand the machining precision and the surface finish. Results on Polyurethane have been analyzed only at a qualitative level, since the coarse quality of results make the process unsuitable for machining on the type of Polyurethane analyzed. As for the milling process, there are ongoing experiments on different types of Polyurethane. The results of the analyses will be better explained in the Section 4.1.

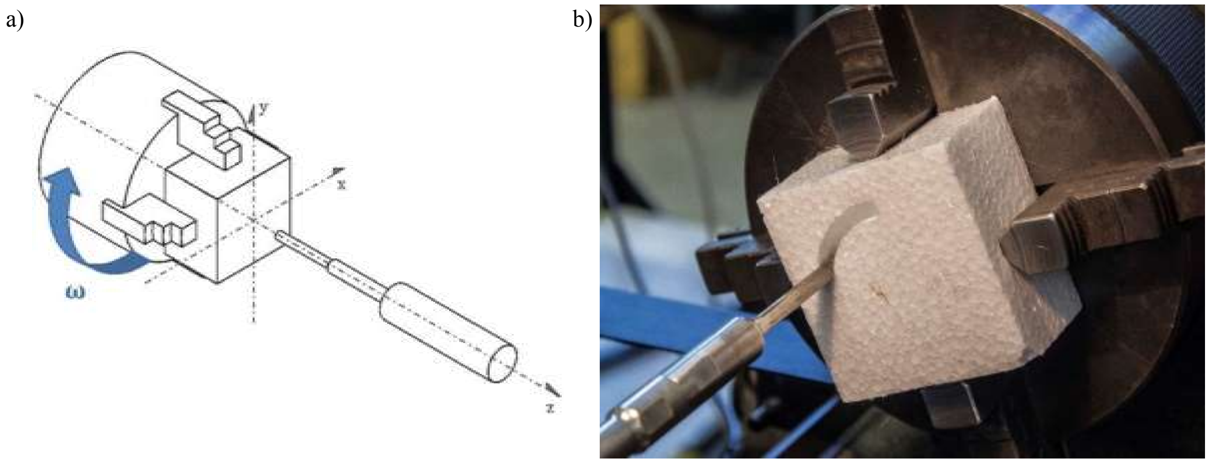


**Figure 6.** Scheme of the setup for the ultrasound machining on lathe (a) and the real setup (b). Because of the dimensions of the sonotrode, the only operation possible was the face grooving.

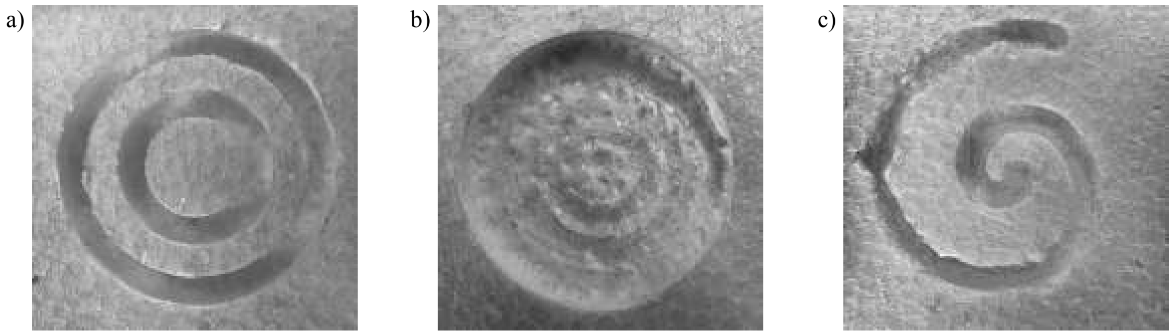


**Figure 7.** Shapes created on Polystyrene: circles (a), cylinder (b) and spiral (c).

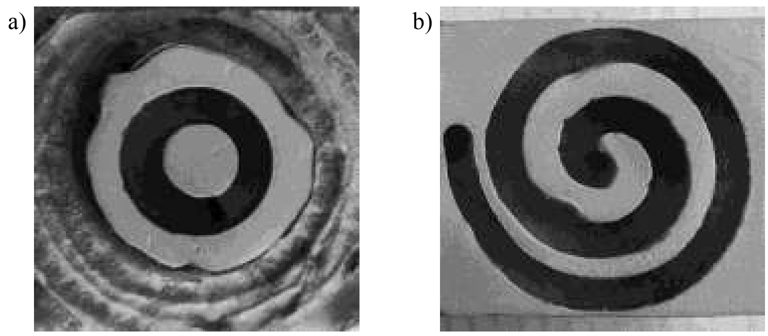


**Figure 8.** Shapes created on Polyurethane samples: cylinders (a) and spiral (b). The quality of the machined piece is coarse.

## 2.3. Optical scanner for dimensional analysis

In this paper, an optical scanner based on an active stereo vision approach (Figure 9) has been designed in order to acquire manufactured sample models [16]. A two-axis platform structure, including rotating and tilting movements, has been assembled by using two stepper motors having a resolution of 400 steps per round. The optical sensor (Figure 9) is composed of a monochrome digital CCD camera (1,280 × 960 pixels) and a multimedia white light DLP projector (1,024 × 768 pixels). A multi-temporal Gray Code Phase Shift Profilometry (GCPSP) method is used for the 3D shape recovery. A sequence of vertical light planes is projected onto the model to be reconstructed. The planes are defined by black and white fringes with time variable period. Each acquired pixel by the camera is characterized by a light intensity that can be either bright or dark, depending on its location in the respective projected image. A binary code (0, 1 with n bit) is assigned to each pixel, where n is the number of the projected stripe patterns, and the values 0 and 1 are associated to the intensity levels, i.e. 0 = black and 1 = white. This encoding procedure provides $l = 2n-1$ encoded lines. The 3-D coordinates of the observed scene point are then computed by intersecting the optical ray from the camera with the projected plane. The geometry of the hardware set-up, the camera ray direction and the plane equation of the corresponding stripe are known by a preliminary calibration step. The methodology provides $n_p = l_h \times l_v$ encoded points, where $l_h$ is the horizontal resolution of the projector while $l_v$ is the vertical resolution of the camera. The whole measurement is obtained by collecting 3D surface data of sample models from various directions. Different views are automatically aligned with reference to a common coordinate system on the basis of the controlled rotating axes, exploiting a calibration procedure which relate turntable positions with respect to the common reference system [17]. The combination of two distinct controlled axes allows a reliable acquisition of shape details, since different viewing directions better handle occlusion problems and undercut areas. The vision system has been configured for a working distance of 300 mm and a working volume of 100 mm × 80 mm × 80 mm (width × height × depth). The scanner is capable of measuring about 1 million 3D points with a spatial resolution of 0.1 mm and an overall accuracy of 0.01 mm [17].

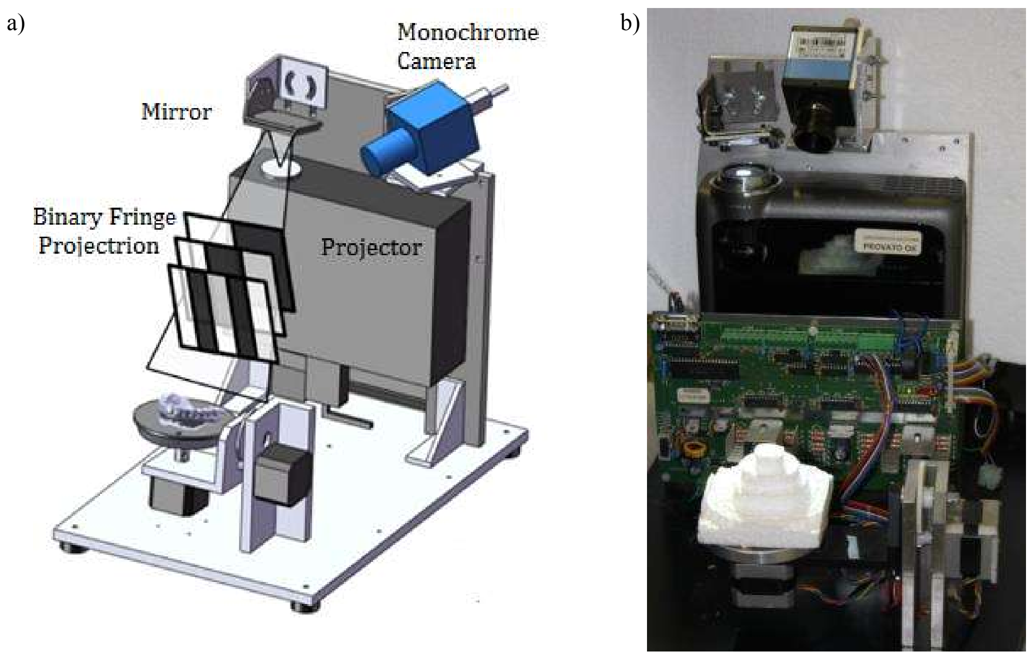


**Figure 9.** Scheme of the assembled optical dental scanner (a) and real setup (b).

## 2.4. Material analysis setup

Control of polystyrene and polyurethane surface properties is very important for understanding the characteristics of the material and the effects of working principle on material. The aim of this work is to analyze the modification of polymer surface, as a consequence of a thermal alteration and an ultrasonic machining. Also underwater machined surfaces are analyzed, even if this working principle was not applied in the manufacturing processes presented in this paper. However, the authors believe that it is an important result to present, since it is currently exploited for ongoing research activities.

The Scanning Electron Microscope (SEM) used to analyze the difference between standard and machined surfaces is a JEOL JSM 5600LV. This is a high vacuum and partial vacuum (10 Pa-10-4 Pa) SEM with secondary electron detector based on the scintillator-photomultiplier design of Everhardt and Thornley.

The SEM provides an image of surfaces and is capable of both high magnification and good depth of field. Unlike a light microscope, the SEM uses electrons instead of white light to view the specimen, so that you can magnify over 100,000 times. In SEM, the electron beam scans across the specimen surface point by point. The signal collected from each point is used to construct an image on the display, with the cathode ray tube beam and the column beam following a synchronized scanning pattern. This means the displayed image is the variation in detected signal intensity as the column beam is scanned across the sample.

## 3. Analysis of the results

The following subsections present the results of dimensional analyses and material analyses. The first ones help in understanding the precision gathered with the ultrasound machining, while the material analyses focus on the physical principle behind the process.

### 3.1. Dimensional analysis

Data from optical scanner have been acquired and a comparison was made based on the results of interest. Some analyses are at quantitative and qualitative level: the milled pyramid (Figure 4b) was analyzed to compare the overall machining quality, the milled circles (Figure 7a) were analyzed for evaluating the lateral precision, while the grooved cylinder (Figure 7b) was used for evaluating the precision of the bottom surface. Other types of analyses were only at a qualitative level, like the spiral sample both on Polystyrene and Polyurethane. The spiral (Figure 7c and Figure 8b) allows understanding how heat and speed of the sonotrode affect the quality of the surface. The rotational speed around the center of rotation O (Figure 10) was kept constant and was 0.5 rpm for both the samples. As in all the turning operations, the closer the tool is to the center of rotation, the lower the tangential speed is. Considering the spiral on Polystyrene, and referring to Figure 10 and Table I, it is evident that when the tangential speed decreases, the surface quality is improved. On the other hand, also the contribution of heat has to be taken into account, since when the machining operation starts, the temperature of the sonotrode is the ambient temperature, and increases during the manufacturing process. In Figure 10, the part of spiral from A (initial point) to C creates poor quality borders, even if the quality progressively increases while getting closer to the point C. From the point C to the final point of the machining process, the quality of the borders can be considered satisfactory.

Considering the spiral created on the Polyurethane block (Figure 11), it appears that during the initial part of the machining process (part from A to B) the quality of the machined part is good, but it gets worse in the point C. This is due to the high temperature reached by the sonotrode, which makes material melting even if it is not in contact with the sonotrode.

The comparison between the CAD model of the pyramid and the manufactured object is shown in Figure 12. If compared with traditional machining operations on conventional materials, the results appear to be unsatisfying. There are few considerations to take into account: the first one, and most important, is that the interface between the sonotrode may have not been connected in a tough way to the robot. This was necessary not to damage the instrument, which does not belong to the department. The second matter is the calculation of trajectories: as already mentioned in Section 2.1, the software used for the calculation of trajectories was set for machining operations using conventional machining tools. Furthermore, the fillet radius was not considered in the CAD model, but it was created because of setting parameters for conventional machining operations.

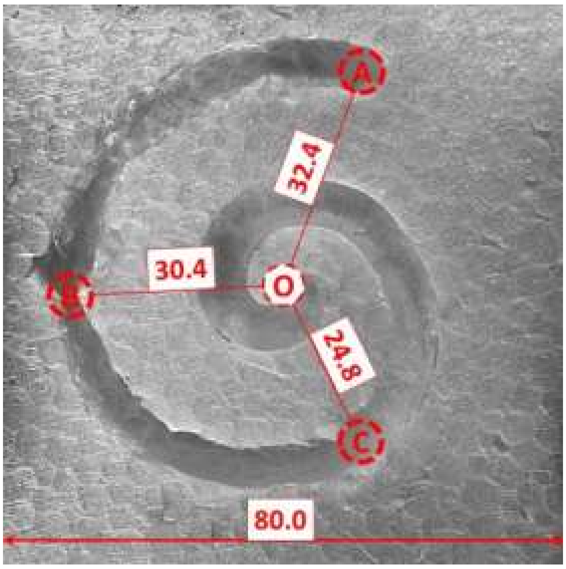


**Figure 10.** Spiral on Polystyrene block with highlighted significant points and measures [mm]: center of rotation (O), initial point (A), point where the material has been torn (B) and point from which the machining operation is satisfactory (C).

**Table I.** Measures and values of machining parameters, referring to Figure 10.

| Point (Figure 10) | Rotational speed [rad/s] | Distance from the Center (O) [mm] | Tangential speed [mm/s] |
|---|---|---|---|
| A | π | 32.4 | 101.8 |
| B | π | 30.4 | 95.5 |
| C | π | 24.8 | 77.9 |

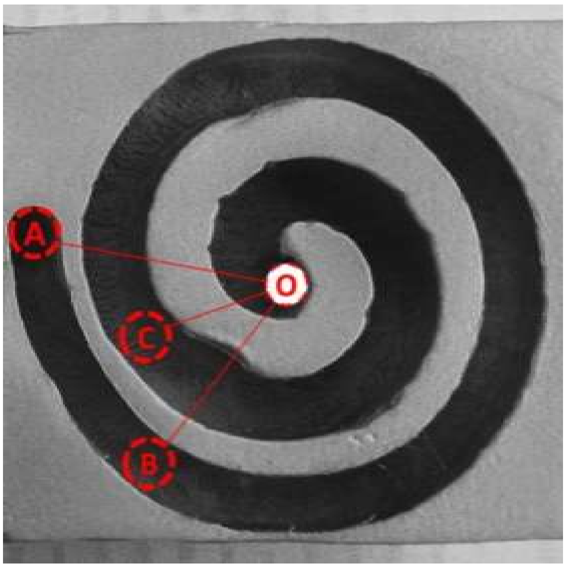


**Figure 11.** Spiral on Polyurethane block with highlighted significant points: center of rotation (O), initial point (A), point where the material starts melting even if not in contact with the sonotrode (B) and point from which the machining quality worsens (C).

The fillet radius has been created starting from the reverse engineering analysis, but these areas lose their importance in the comparison analysis. The last consideration regards the machined material itself, since its high level of non-homogeneity lowers the surface precision level. The percentage of measured points versus deviation values are plotted in

Figure 13, and clearly show that the maximum precision that can be gathered is coarse. However, because of the problems explained above, more experiments with different interfaces and different trajectories have to be done before a conclusion can be made.

The circular groove shown in Figure 7a has been used to evaluate the lateral precision of the ultrasound machining process. The comparison between theoretical circular surfaces and the real machined surface is shown in Figure 14, where a section of the specimen is analyzed. Figure 15 presents the deviation of the specimen from the CAD model versus percentage of points for the section shown in Figure 14. Compared to the results of milling operations, the number of points having a high deviation from the theoretical shape is considerably decreased. This result is considered positive at this stage of the study, but will have to be tested with different working parameters, in order to understand how they influence the shape precision.

Considering now the cylinder, the comparison between the ideal cylindrical surface and the manufactured object is used to evaluate how the working parameters, especially the feed ratio, affect the bottom surface. The results for a section of the cylinder are shown in Figure 16. Figure 17 presents the deviation of the specimen from the CAD model versus percentage of points for the section shown in Figure 16. Compared to the analysis of the milled pyramid, a higher number of points has a smaller deviation from the theoretical shape, and the result can be considered encouraging at this step of the process study.

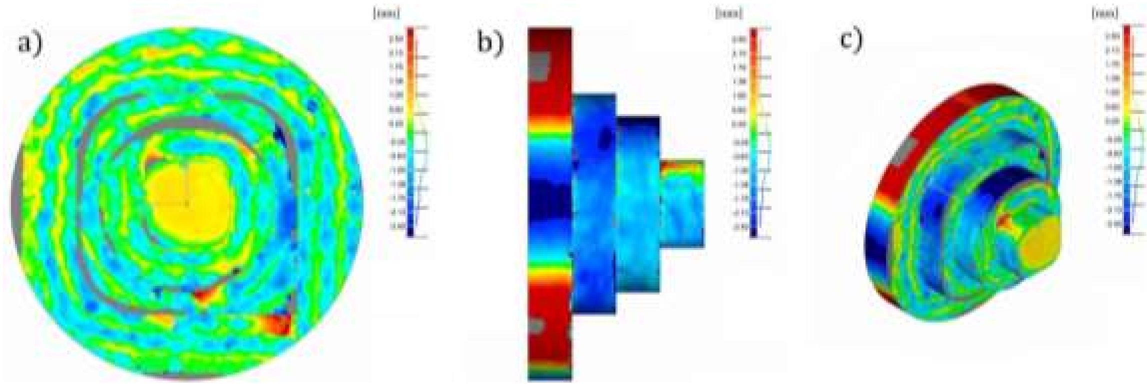


**Figure 12.** Comparison between the manufactured pyramid and the CAD model: top (a), side (b) and isometric (c) views.

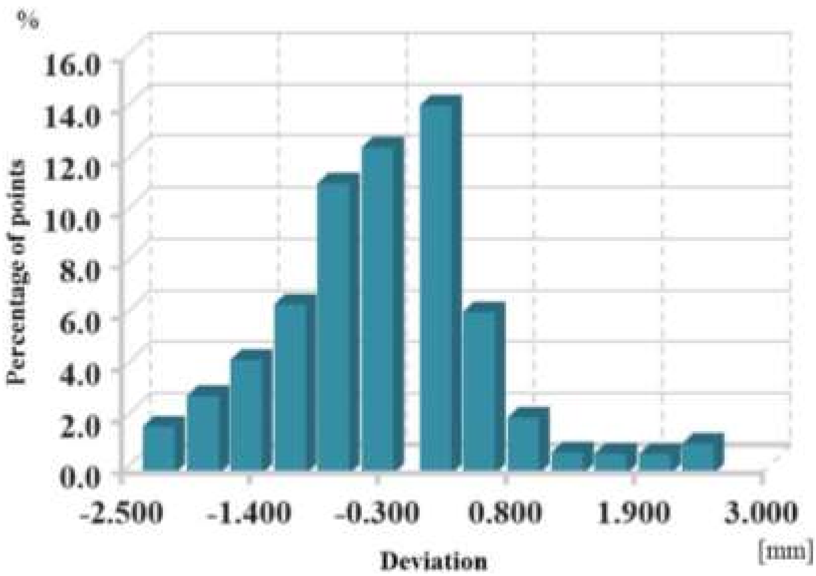


**Figure 13.** Deviation of the specimen from the CAD model versus percentage of points for the grooved cylinder.

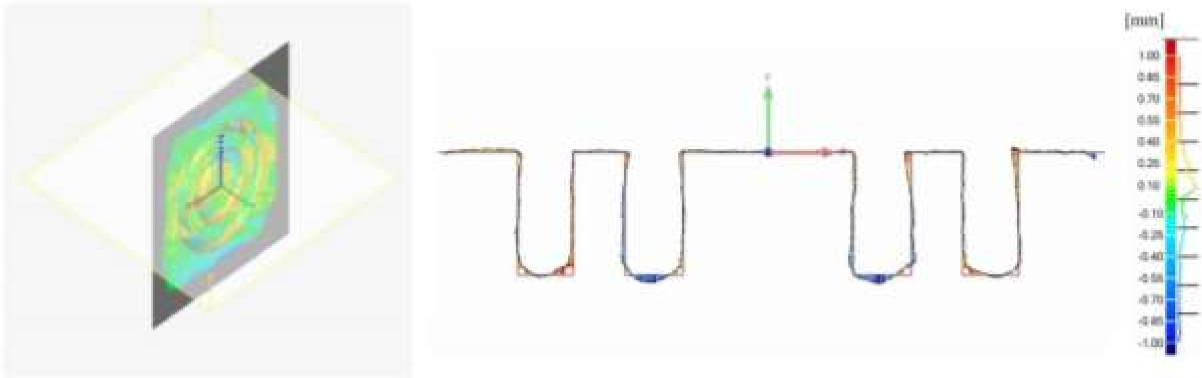


**Figure 14.** Comparison between perfectly circular surfaces and the real machined surface for the section of the specimen indicated on the left.

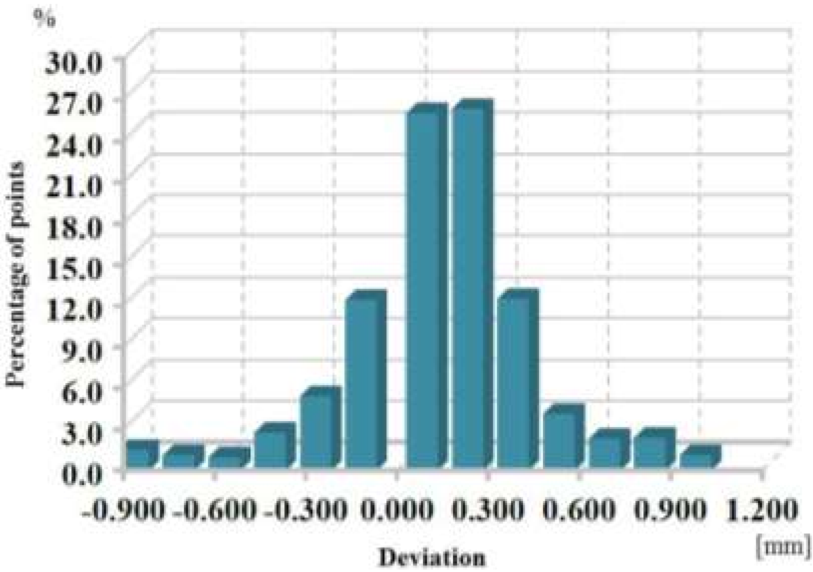


**Figure 15.** Deviation of the specimen from the CAD model versus percentage of points for the grooved circles for the section illustrated in Figure 14.

Figure 18 highlights the trajectories of the axis of the sonotrode: the blue areas refer in fact to the frontal part of the probe, while the red parts have not been properly machined. Other tests will have to be done using different working parameters, especially the feed ratio will have to be decreased in order to gather an improved bottom surface of the cylinder.

Before concluding this section, it is important to highlight how the comparative analysis values significantly vary between the shape machined with the milling manufacturing and the ones obtained using the lathe. In fact, while the deviation of the pyramid from the CAD model presents a high number of points significantly distant from their ideal position, the percentage and the maximum error decrease significantly for the lathe-machined workpieces. This allows the authors to consider that the working parameters affected significantly the results of the machining process, and encourage to continue the experimental activity.

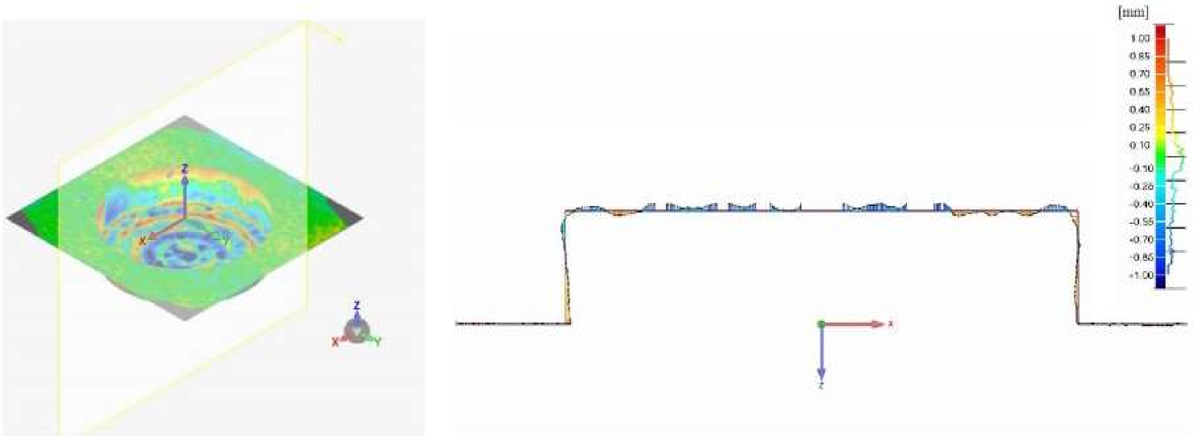

Figure 16. Deviation of the bottom surface of the grooved cylinder from an ideal planar surface.

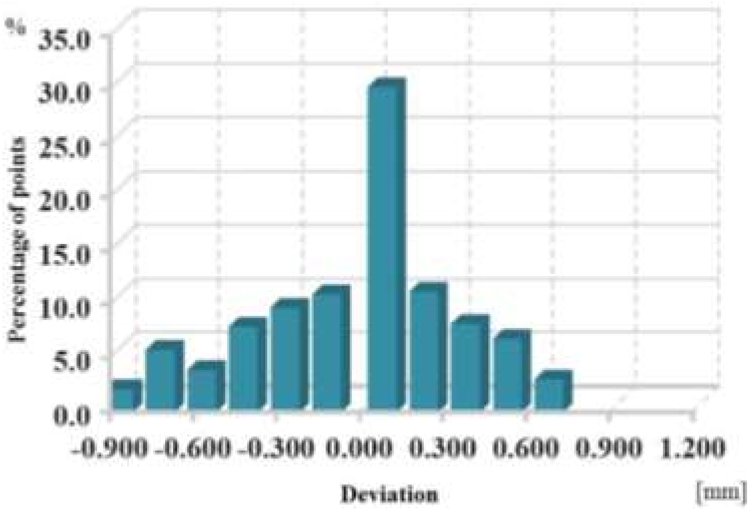


**Figure 17.** Deviation of the specimen from the CAD model versus percentage of points for the grooved cylinder for the section illustrated in Figure 16.

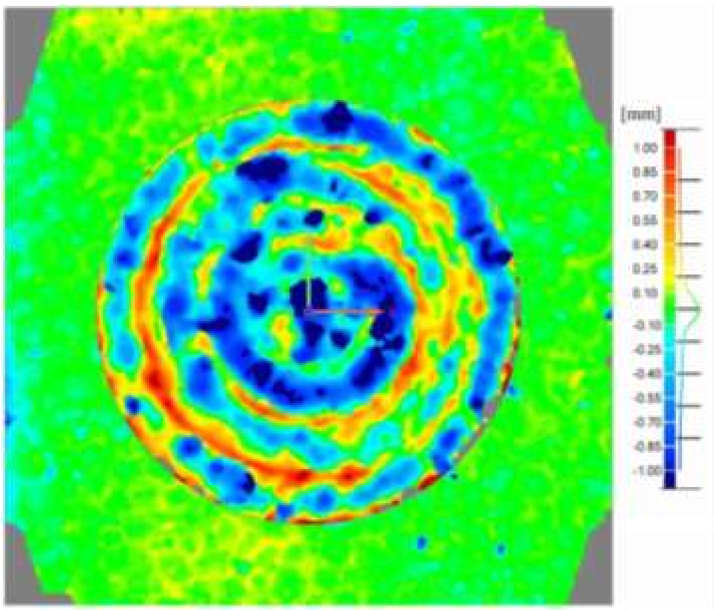

**Figure 18.** Comparison of the whole bottom surface of the grooved cylinder. The blue areas indicate where the axis of the sonotrode has passed. The deviation values are in millimeters.

## 3.2. Material Analysis

This section aims at validating the working principle of ultrasound machining. In [1] and [2] the authors supposed that the working principle was a combination of both thermal and mechanical effects.

Images shown in Figure 19, thanks to the signals that derive from electron-sample interactions, reveal information about the external morphology of the samples of Polystyrene:

a) *untreated Polystyrene* presents a regular structure, with spherical profiles;
b) *thermal altered Polystyrene* shows a stretched structure, with pseudo-circular holes;
c) *in-air machined Polystyrene* has a spread texture, in consequence of the fact that polystyrene begins to melt;
d) *underwater machined Polystyrene* shows a squamous structure, due to the rapid solidification of melted material in contact with water.

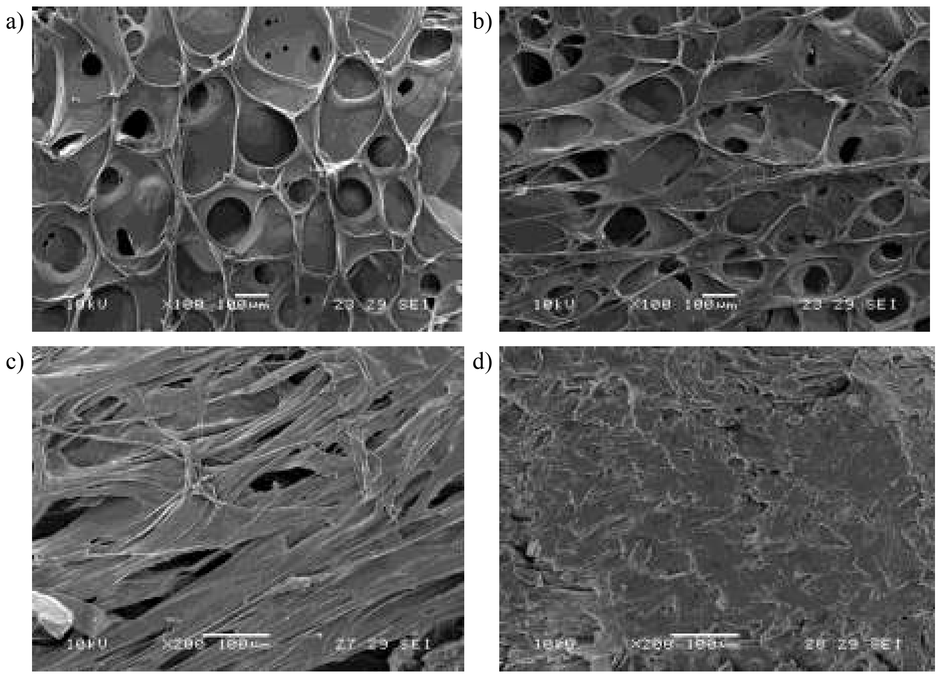


**Figure 19.** Polystyrene SEM analysis: (a) untreated, (b) thermal altered, (c) in-air machined and (d) underwater machined Polystyrene samples.

Conducting the same analyses for Polyurethane samples, Figure 20 reveals that:

a) *untreated Polyurethane* presents a smoothed face, with few irregular holes;
*b) thermal altered Polyurethane* presents a regular hexagonal structure;
*c) in-air machined Polyurethane* has a soldered texture, due to the spread of melted polyurethane;
*d) underwater machined Polyurethane* reveals an indented structure, by reason of the rapid solidification of underwater processed material.

From the analysis of the SEM images, it is clear that heat is not the only working principle, otherwise the structure would have been similar to the one shown in Figure 19b and Figure 20b. Since the texture of in-air machined material is the one shown in Figure 19c and Figure 20c, the mechanical action has an important role in spreading the softened material over the walls of machined shapes. Figure 19d and Figure 20d are useful for understanding the action of water in case of underwater machining, which will be analyzed in a future work.

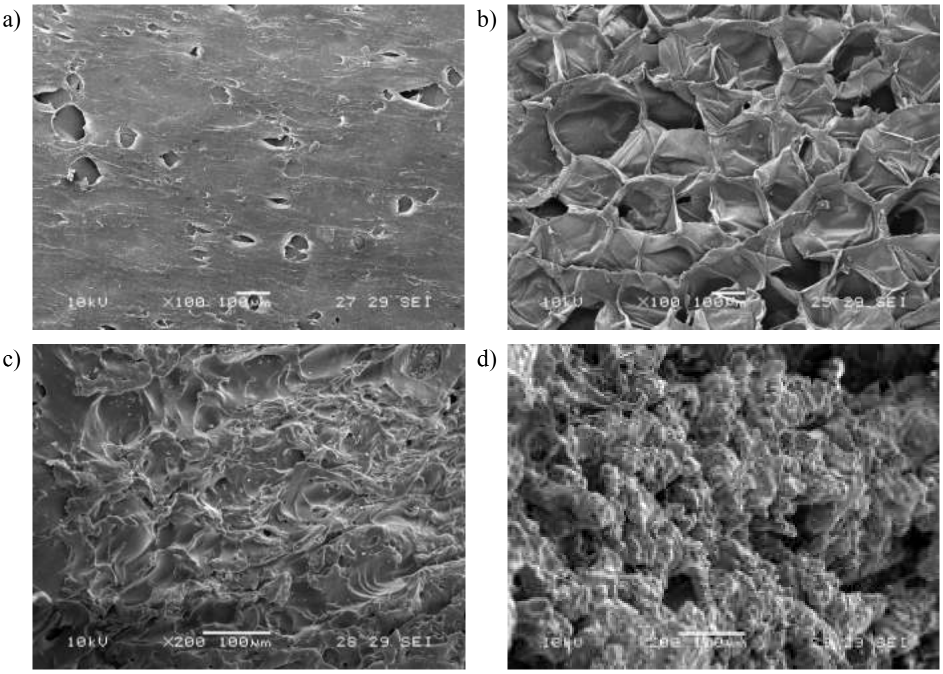


**Figure 20.** Polyurethane SEM analysis: (a) untreated, (b) thermal altered, (c) in-air machined and (d) underwater machined Polyurethane samples.

## 4. Conclusions

The paper has highlighted the possibility of using ultrasound technologies for shaping operations on foam like material, focusing mainly on Polystyrene. This study is still a first step toward enhancing the understanding of procedures for the achievement of well-shaped workpieces. This has been possible thanks to dimensional analyses comparison and material analyses. The first ones have been helpful for understanding the quality of the manufacturing process, while the second analyses made possible to understand the physics behind the manufacturing process.

The dimensional analyses revealed that grooving operations performed on Polystyrene have a good precision level, if considered together with the limitations of the physical properties of the materials shaped. Vice versa the milling operation has some clear limitations. The most important limitation lies in the trajectories calculated by the software for the Polystyrene sample, while for Polyurethane the limitation is due to the physical properties of the material itself.

Future work will concentrate in solving these problems, and will focus on improving the manufacturing quality of a wider set of materials, and on the study of underwater machining operations. The authors are currently investigating the possibility of using a different type of Polyurethane, commonly known as blue foam, for the creation of workpieces with improved dimensional precision.

## Acknowledgments

The authors wish to gratefully acknowledge F. Antonelli, G. Moretti and E. Peroni, for their valuable help in manufacturing of the devices and in supporting the testing phases of the work. They also thank G. Vozzi and S. Balestrino (Research Center “E. Piaggio”), C. de Maria (FabLab Pisa) and R. Ishak (DICCISM) for their ongoing collaboration within this research activity. Finally they also acknowledge the contribution of Nivol s.r.l. for making available their 3D scanners, and Gruppo Scienzia Machinale for the support in the control phases of the robot.

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