POLITECNICO DI MILANO (LECCO CAMPUS)

School of Industrial and Information Engineering

Master of Science in Mechanical Engineering

DESIGN OF ULTRASONIC SHOT PEENING DEVICE

Supervisor: Prof. MARIO GUAGLIANO

Co-Supervisor: Dr. SARA BAGHERIFARD

Author: BEHROOZ SARABI (770661)

2016-2017

Table of Contents

Table of Contents 2
List of Figures 4
List of Tables 6
List of Drawings 7
Abstract 8
Astratto 9
1. Introduction to shot peening 10
1.1 What is shot peening 10
1.2 Air blast shot peening 11
1.3 The mechanics of shot peening 13
1.4 Applications of shot peening 16
1.5- Shot peening and surface grain refinement 17
1.6 Different methods of shot peening aimed at grain refinement 19
1.6.1 Ultrasonic shot peening method 19
1.6.2 High energy shot peening method 20
1.6.3 Surface nanocrystallization and hardening method 20
1.6.4. Severe shot peening 20
2. Ultrasonic shot peening 22
2.1 What is Ultrasonic Shot Peening 22
2.2 A brief history on ultrasonic shot peening 24
2.3 Applications of ultrasonic shot peening 24
2.4 A brief introduction on the working mechanism of ultrasonic shot peening devices 25
2.5 How ultrasonic shot peening affects the surface of the material 26
2.6 Parameters affecting the result on the workpiece 28
3. Design of ultrasonic shot peening device 29
3.1 Description of the design approach 29
3.2 Samples to be used at room temperature 30

3.2.1 Almen strip sample 30
3.2.2 ASTM E8/E8M – 09 plate tensile test sample 31
3.2.3 ASTM E466-15 rod-shaped tensile test sample 32
3.3 Chamber design 34
3.3.1 Chamber material selection 34
3.3.2 Chamber preliminary shape and dimensions selection 35
3.3.3 Modification of the design of the chamber to match all three samples 37
3.3.4 Bearing selection for the chamber 45
3.3.5 Fittings design for the chamber 45
3.4 Choice of shots 49
3.4.1 Material of shots 49
3.4.2 Dimension and number of shots 50
3.5 Choice of sonotrode 51
3.5.1 Amplitude of the sonotrode 51
3.5.2 Frequency and material of the sonotrode 52
3.6. Solution for rotating the E466-15 rod-shaped sample 53
3.7 Vacuuming solution 54
3.8 Three-dimensional rendering of our ultrasonic shot peening device 55
4. Possible future developments: Design of warm ultrasonic shot peening device for magnesium alloy sample 59
4.1 Sample to be warm ultrasonic shot peened 60
4.2 Chamber shape-design for the warm ultrasonic shot peening device 60
4.2.3 Explanation of the working mechanism of our warm ultrasonic shot peening chamber 61
4.3 Chamber material selection for the warm ultrasonic shot peening device 73
5. Conclusion and suggestions 74
References 76

List of Figures

Figure 1.1 [2] – schematic of shot peening process 10
Figure 1.2 [9] – schematic illustration of air blast shot peening. 11
Figure 1.3 [17] – Schematic illustration of sand blasting process 12
Figure 1.4 [18] – shot peening mechanics 13
Figure 1.5 [19] – typical distribution of compressive residual stresses caused by shot peening 14
Figure 1.6 [21] – The process to obtain a single arc height on a saturation curve 15
Figure 1.7 – Schematic saturation curve (SAE J443, 2003) 16
Figure 1.8 [10] – Arrangement of grain boundaries in nanostructured layers 18
Figure 2.1 [32] – Schematic illustration of the ultrasonic shot peening set-up...23
Figure 2.2 [55] – Ultrasonic shot peening Mitsubishi set-up.............................23
Figure 2.3 [58] – main parts of a typical ultrasonic shot peening device made by Sonats Company..26
Figure 2.4 [59] – Schematic view of different surface layers (according grain size) generated on the workpiece after ultrasonic shot peening..........................27
Figure 3.1 – 3D rendering of the N-type Almen strip sample 30
Figure 3.2 [21] – Standard condition for Almen strip holding fixture................31
Figure 3.3 – 3D rendering of ASTM E8/E8M – 09 sample...............................31
Figure 3.4 – 3D rendering of ASTM E466-15 rod sample 32
Figure 3.5 – 3D rendering of the modified chamber..38
Figure 3.6 – Almen strip fixed to the holed lid (internal view) 39
Figure 3.7 – Almen strip fixed to the holed lid (external view)..........................39
Figure 3.8 – Chamber preparation (sliding appropriate fittings in place) for Almen strip sample treatment 46
Figure 3.9 – Chamber ready for Almen strip sample treatment..........................46
Figure 3.10 – Chamber ready for E8/E8 sample treatment.................................47
Figure 3.11 – Chamber ready for rod-shaped sample treatment.........................47
Figure 3.12 – 3D render of our USP device; Almen strip treatment mode (view 1) 55
Figure 3.13 – 3D render of our USP device; Almen strip treatment mode (view 2) 56
Figure 3.14 – 3D render of our USP device; Almen strip treatment mode (view 3) 56
Figure 3.15 – 3D render of our USP device; E8/E8 sample plate treatment mode (view 1) 57

Figure 3.16 – 3D render of our USP device; E8/E8 sample treatment mode (view 2) 57
Figure 3.17 – 3D render of our USP device; E466-15 sample treatment mode (view 1) 58
Figure 3.18 – 3D render of our USP device; E466-15 sample treatment mode (view 2) 58
Figure 4.1 – WUSP peening chamber....61
Figure 4.2 – Working stages of the WUSP chamber; Stage 1: Empty chamber, ready to put in the sample workpiece....62
Figure 4.3 – Working stages of the WUSP chamber; Stage 2: Sample workpiece (green) inserted inside the chamber. 63
Figure 4.4 – Working stages of the WUSP chamber; Stage 3: The safety gate and the lid are closed....63
Figure 4.5 – Working stages of the WUSP chamber; Stage 4: The chamber is vacuumed via the vacuum tube....64
Figure 4.6 – Working stages of the WUSP chamber; Stage 5: Vacuum gate is closed....64
Figure 4.7 – Working stages of the WUSP chamber; Stage 6: The electric heaters are turned on and the sample workpiece reaches the desired temperature, ready to be shot peened....65

List of Tables

Table 3.1 – Chamber: material selection..35
Table 3.2 – Chamber: shape and dimension selection 37
Table 3.3 – Shots: material selection 49
Table 3.4 – Shots: diameter and number selection 50
Table 3.5 – Sonotrode: amplitude selection...52
Table 3.6 – Sonotrode: frequency and material selection 53

List of Drawings

Drawing 3.1 – Workpiece samples for treatment in room temperature 33
Drawing 3.2 – Chamber for room temperature conditions 40
Drawing 3.3 – Holed lid 41
Drawing 3.4 – Un-holed lid 42
Drawing 3.5 – Bolt for Almen strip 43
Drawing 3.6 – Nut for Almen strip 44
Drawing 3.7 – Fittings (Almen, E8/E8, Rod) 48
Drawing 4.1 – WUSP chamber; Front view 66
Drawing 4.2 – WUSP chamber; Details A, B & C 67
Drawing 4.3 – WUSP chamber; Left view 68
Drawing 4.4 – WUSP chamber; Top view 69
Drawing 4.5 – WUSP chamber; Isometric view 70
Drawing 4.6 – Lid; Safety gate (for WUSP chamber) 71
Drawing 4.7 – Heater; Vacuum gate (for WUSP chamber) 72

Abstract

This thesis presents the design of an ultrasonic shot peening device. To achieve this, in the first place, we did a close study of the literature and a wide research on relevant industrial products, to acquire information on both the ultrasonic shot peening treatment (including influencing parameters, treatment mechanics, etc.) and the design of its device (including device components, design parameters regarding each component, available range for design parameters, etc.). Considering the specific treatment requirements for each of our sample workpieces, we then started with the design of the device, which consisted of two parts: Designing the peening chamber (the main body of our device) containing lids, various types of fittings, fixtures, etc., and choosing the technical specifications of the other constituting components of our device that needed to be procured (including shots, sonotrode, bearings, electric motor, vacuum chamber, etc.). Our finalized design choices were accompanied by justifications, comparing our choice of the product with other available choices. Eventually, for a better visualization of our complex-shaped design, three-dimensional CAD renderings of our device were provided in each of its treatment modes. As a possibility for further development of our device, we proposed a design model for a brand-new technology called warm ultrasonic shot peening (ultrasonic shot peening at high temperatures for magnesium sample).

Keywords: ultrasonic shot peening, USP, surface material attrition treatment, SMAT, warm ultrasonic shot peening, WUSP, magnesium ultrasonic shot peening, ultrasonic shot peening chamber design, CAD, model, geometry

Astratto

Questa tesi fornisce la progettazione di un dispositivo di pallinatura ultrasonica. Per raggiungere questo obiettivo, innanzitutto, abbiamo fatto un attento studio della letteratura ed un'amplia ricerca sui prodotti industriali rilevanti, per acquisire informazioni sia sul trattamento di pallinatura ultrasonica (tra cui i parametri che influenzano il processo, le meccaniche del trattamento, etc.), che sulla progettazione del dispositivo (tra cui i componenti del dispositivo, i parametri della progettazione di ogni componente, la gamma disponibile per i parametri di progettazione, etc.). Considerando i requisiti specifici del trattamento di ciascuno dei nostri esemplari in lavorazione, abbiamo poi iniziato con la progettazione del dispositivo, che è avvenuta in due fasi: progettazione della camera di pallinatura (il corpo principale del dispositivo), contenente coperchi, diversi tipi di raccordi, e apparecchiature varie, e le scelte specifiche degli altri componenti del nostro dispositivo di cui è necessario l'acquisto (compresi i pallini, il sonotrode, i cuscinetti, il motore elettrico, e la camera sottovuoto). Le nostre scelte progettuali finali sono motivate, e per ognuna è fornito un confronto con le altre opzioni disponibili. Infine, per meglio rendere la complessità del nostro design, sono stati prodotti dei rendering CAD del nostro dispositivo in ciascuna delle sue modalità di trattamento. Come possibile sviluppo futuro del nostro dispositivo, abbiamo proposto un modello di progettazione per una tecnologia originale chiamata pallinatura ultrasonica calda (pallinatura ultrasonica alle alte temperature per campione di magnesio).

Parole Chiave: pallinatura ultrasonica, USP, SMAT, pallinatura ultrasonica calda, WUSP, pallinatura ultrasonica di magnesio, progettazione della camera di pallinatura ultrasonica, CAD, modello, geometria

1. Introduction to shot peening

1.1 What is shot peening

Shot peening is a process in which by bombarding the surface of metals and composites with shots (made of diverse materials and dimensions), a compressive residual stress layer is produced on the surface of the material. As a result, plastic deformations will be created by these impacts, and thus a change in mechanical properties of the material surface would be obtained. Shot peening is a cold working process and has widespread industrial applications. [1]

Figure 0.1 [2] – schematic of shot peening process

The main application of shot peening is to delay the propagation of micro-cracks in the surface. If the induced residual stress field is compressive, these cracks do not propagate in the material. [3] Therefore, shot peening is very useful to prevent fatigue and stress corrosion failures and can be helpful to prolong product life for the part under fatigue stress.

1.2 Air blast shot peening

Air blast shot peening is the conventional method of shot peening. In air blast shot peening by use of compressed air, the shots are blasted to the surface of the workpiece. [4] [5] [6] [7] In this method, the distribution of the velocity of the shots is narrow and the hitting direction of shots are almost normal to the workpiece surface. [5] The mechanically enhanced surface layer is generated by use of higher shot velocity and bigger coverage compared to conventional methods. [8] The process parameters affecting the results in air blast shot peening are shot size, shot materials and air pressure. The scale commonly used to measure shot peening performance is the Almen scale. However, it may not be applicable in case we need to measure the performance of each parameter in terms of shot size, shot material and velocity separately. This is because this scale is an index used for summarizing the general effect of multiple treatment parameters involved in production of nanocrystal in the surface, without being capable to considering the significance of each factor separately. A schematic illustration of the air blast shot peening equipment is illustrated in Figure 1.2 [9]. [10]

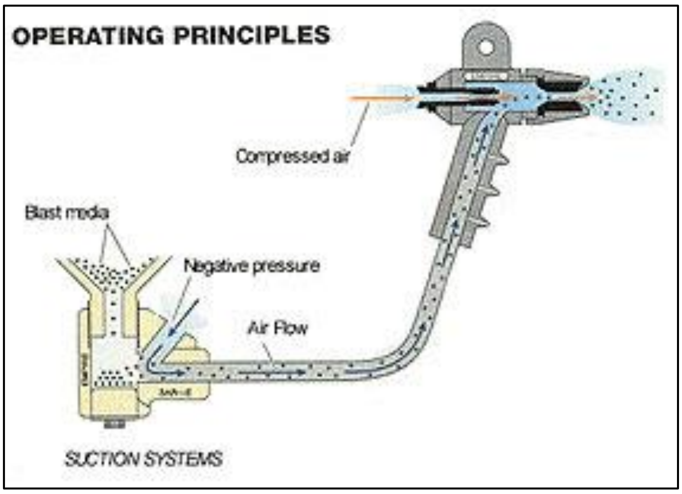


Figure 0.2 [9] – schematic illustration of air blast shot peening.

Some variations of ABSP such as sand blast shot peening (also called shot blasting) have been occasionally used in the industry mainly for the purpose of surface cleaning. In sand blasting by hitting multiple times the surface of the material with high speed particles, some changes in the surface is caused:

elimination of the surface oxide scale and creation of local plastic deformation. Furthermore, in the subsurface region, a layer of compressed residual stress is normally produced. Changes in the microstructure of the surface layer have been observed and reported by some articles throughout this process. [11] [12]

A big difference between sand blasting method and the ABSP, is the geometry and dimension of the shots being random in sand blasting, and often having smaller shot size compared to air blast shot peening method. The orientation of the nanograins will be usually accidental in sand blasting after the annealing treatment, and the nanograins will have sharper grain boundaries which is caused by the primarily formation of dislocation web. Severe plastic deformation, and therefore, severe density dislocations can be also observed in the surface layer of the sandblasted workpiece. The annealed sandblasted surface shows and improvement of surface quality regarding mechanical properties, in comparison to the sandblasted surface. [13] [14] The reason for this can be explained by the change nanograins' characteristics after annealing.

As a surface treatment process, sand blasting is widely used for surface cleaning and corrosion removal. [15] [16] [10]

In Figure 1.3 [17] a schematic presentation of the sand blasting procedure is presented.

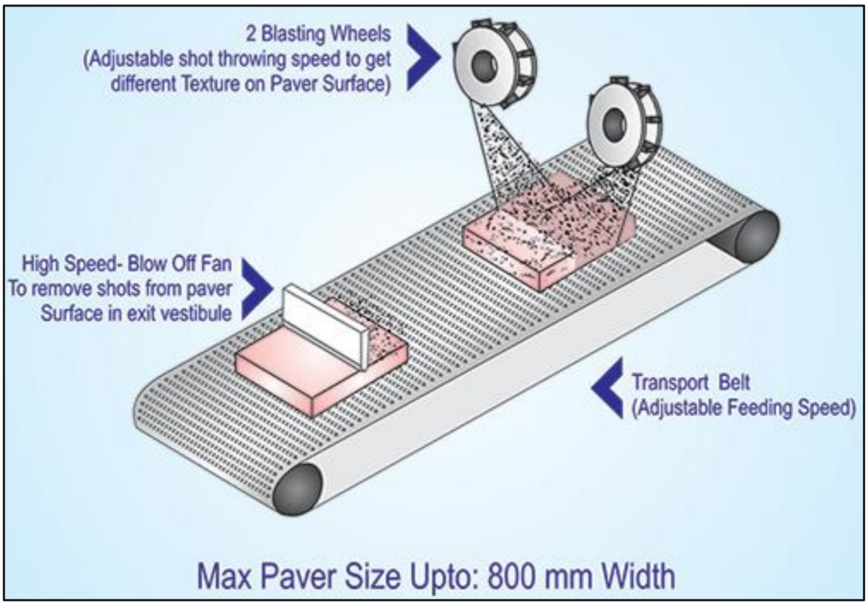


Figure 0.3 [17] – Schematic illustration of sand blasting process

1.3 The mechanics of shot peening

Shot peening works by enforcing high residual compressive stress in the surface of the material. By shot peening the surface is plastically deformed, causing changes in the mechanical properties of the surface. The compressive stress is helpful for prevention of crack propagation since cracks cannot advance in the compressive environment that is produced by shot peening.

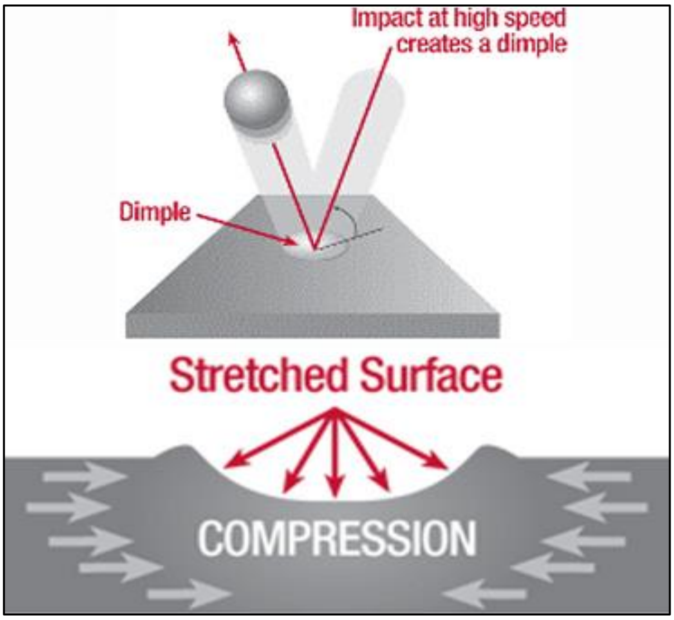


Figure 0.4 [18] – shot peening mechanics

As a result of the impact of each piece of shot on the part, a small indentation is produced, and therefore compressive stresses are generated. The procedure is such that if the surface has been impacted, then the material beneath the induced dimple has been compressed. Shot peening produces not just one dimple but thousands on the surface. Thus, a compressively stressed layer is created beneath the part's surface becomes. [19]

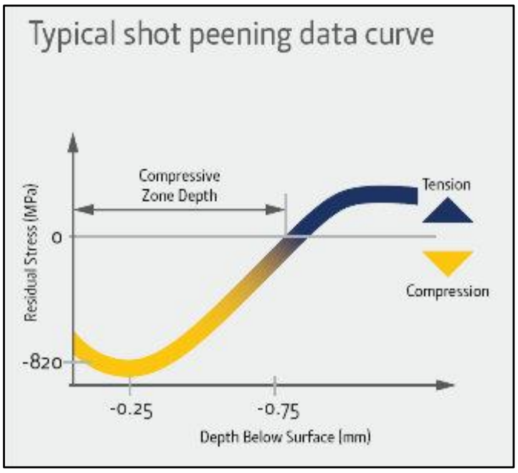


Figure 0.5 [19] – typical distribution of compressive residual stresses caused by shot peening

A key parameter in the shot peening process is Intensity. As the development of the shot peening process advanced, an analog seemed necessary to measure its effects. John Almen realized that shot peening made the exposed surface of sheet metal begin to stretch and bend. The Almen strip was produced by him as a means of measuring the compressive stresses in the strip which was produced by the shot peening operation. He developed a standard process to measure the kinematic energy transferred by the shot stream. SP specifications refer to this energy as intensity at saturation. The measurement of peening intensity is accomplished by determining its effect on standardized test strips, called Almen strips, with a standardized tool, called Almen gage. The method of intensity measurement derived by J.O. Almen has been universally accepted and adopted by engineers in their design consideration. The following items are required in order to determine shot peening intensity: [20] [21]

- Almen test strips
- Almen gage
- test strip holding fixture (Almen holder)

There are three types of Almen strip specified. The standard test strips of spring steel SAE1070 tempered to 44-50 HRC have different thicknesses for usage at different intensity levels (SAE AMS 2432B, 1996; SAE AMS-S-13165, 1997; SAE J442, 2001). Figure 1.6 illustrates how to measure SP intensity with the previously named tools. After the strip has been exposed to the shot stream and removed from the holding fixture, the gage stem is placed against not peened surface. The measured strip deflection represents a single arc height at the given exposure time. [21]

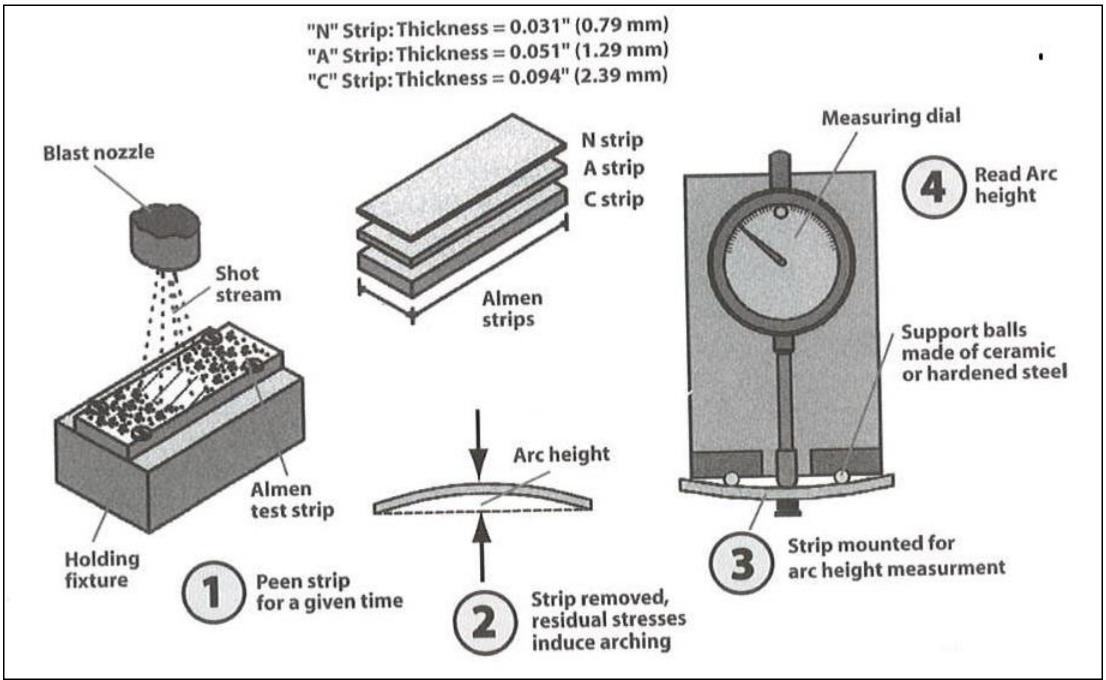


Figure 0.6 [21] – The process to obtain a single arc height on a saturation curve

Intensity is expressed as the arc height of a shot peened test strip at saturation point; and saturation point is defined as the earliest point of the saturation curve that, if the exposure time is doubled, the arc height increases by 10% or less. For determining the intensity of peening process, it is necessary to establish a saturation curve. Establishing a saturation curve is accomplished by peening a series of Almen strips, using different exposure times, with all other SP parameters kept constant. Plotting the arc height deflection of different strips as a function of exposure time will define a curve with the general shape as shown in Figure 0.7. The saturation time (T) is the earliest point on the curve where doubling the exposure time (2T) produces no more than a 10% increase in the arc height. Almen intensity is the particular arc height obtained at saturation time (indicated as T in Figure 0.7). [21]

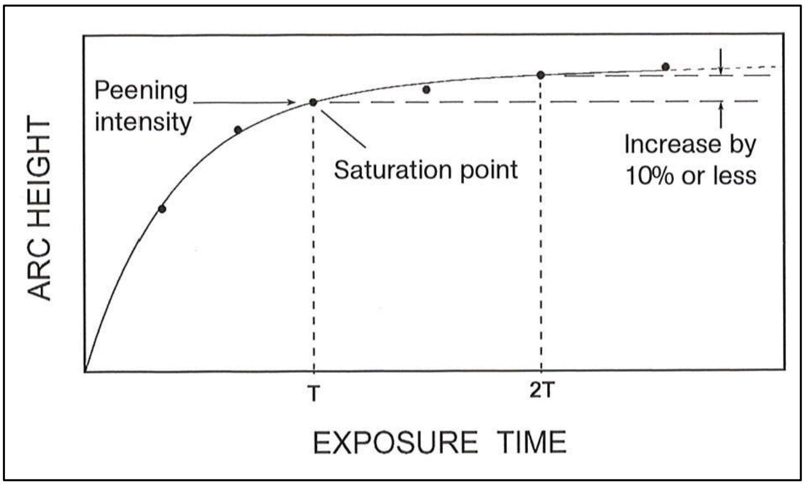


Figure 0.7 – Schematic saturation curve (SAE J443, 2003)

Different peening factors including shot size, shot hardness, shot flow rate, shot velocity, distance and the angle of impact directly affect the intensity of the SP process.

Another key parameter in shot peening is surface Coverage, which is the percentage of the surface that is at least once impacted, and is affected due to the angle of the stream of the shot blast relative to the workpiece surface. The shots arrive at angles that vary, due to the fact that the stream of the shot is cone-shaped. Coverage can be improved by impacting the surface with a series of overlapping passes. However, variations in "stripes" will still exist. It is of high significance to align the axis of the shot stream with the axis of the Almen strip. To produce the desired effect on the surface of the material, it is necessary to optimize the level of coverage that is applied on the material. [22]

1.4 Applications of shot peening

The applications of shot peening to enhance the reliability of machine parts range from increasing their straightening, fatigue strength, formation of machine parts, pretreatment before plating, pretreatment for parts that need to be coated with plastics or metallized, enhancing the stress resistance, corrosion resistance, cracking resistance, etc. [23]. Shot peening has been widely used on cams and camshafts, gear parts, clutch and coil springs, crankshafts, gearwheels, connecting rods, leaf and suspension springs, turbine blades and rock drills. Also in foundries for sand removal, descaling, decorating, and surface finishing of castings, shot peening has been used, as for the manufacturing of steel products such as wire, strip, plates, bar stock and sheets. [1] [24]Shot peening has been also used to produce cosmetic effects. The surface irregularities and unevenness which is resulted from the overlapping of the passes cause light to be dispersed upon reflection. However, shot peening is most widely used for improving the fatigue life.

Shot peening role has been essential in spring production. Especially spring types like compressive springs, extension springs, and leaf springs. The major application of the shot peening in this field has been for engine valve springs, since it has a high cyclic fatigue. In aftermarket valve spring usages, the existence of controlled and multi-step shot peening is crucial to resist the intense surface stresses, which at times outpaces material specifications.

Combined with abrasive blasting, shot peening can be used to apply materials on the surface of the metal. The shots when blasted via a liquid or powder that incorporates the desired surface coating, the effect coats the surface of the material. This method has been used to apply coatings of ceramic. However, the coverage is not very coherent. Another process, which has been named peen plating, was invented by NASA. In this method, Fine powders of material (usually metals or non-metals) are placed onto the surface of the metal by using bead shots of glass as the blast medium. Ceramics that are biocompatible have been applied by this method to biomedical implants. In peen plating, the coating material will be highly heated in the impacts with the shot and the coating should also have powder form, which is a limit, concerning the range of materials that can be used. In order to overcome the heat problem, a method known as temperature moderated-collision mediated coating (TM-CMC) has made possible the use of polymers and antibiotic materials as peened coatings. [25]

1.5- Shot peening and surface grain refinement

Nanocrystal materials (or nanomaterials) which are materials having crystal grains dimensioning up to 100 nm, have had a rapid development in recent years. This is on one hand because they have had application in a wide variety of technological fields including catalysis, ceramics, electronics, biotechnology, magnetic data storage, structural components, etc., and on the other hand, since these materials have improved mechanical properties which differ from their conventional coarse grained polycrystalline crystals. [26] [27]

Considering that most mechanical failures initiate from surface layers of materials, it is expected that producing a nanocrystalline layer on the surface of the material will cause its performance to be globally improved leading it to have superior mechanical properties.

Different types of Severe Plastic Deformation processes have been suggested for producing nanocrystal surfaces, among which, shot peening based techniques have been widely used thanks to its simplicity and applicability for a variety of material types. Researches show that for obtaining nanocrystal materials through severe plastic deformation, it is needed to implement non-homogeneous deformation methods with large strain gradients on the material. [10]

A rearrangement of dislocations during the process has been observed in all these methods: The dislocations, through the process, shift from the interior part of the grains to the boundaries of the grains. In Figure 1.8 a schematic illustration of this defect rearrangement is presented. [10]

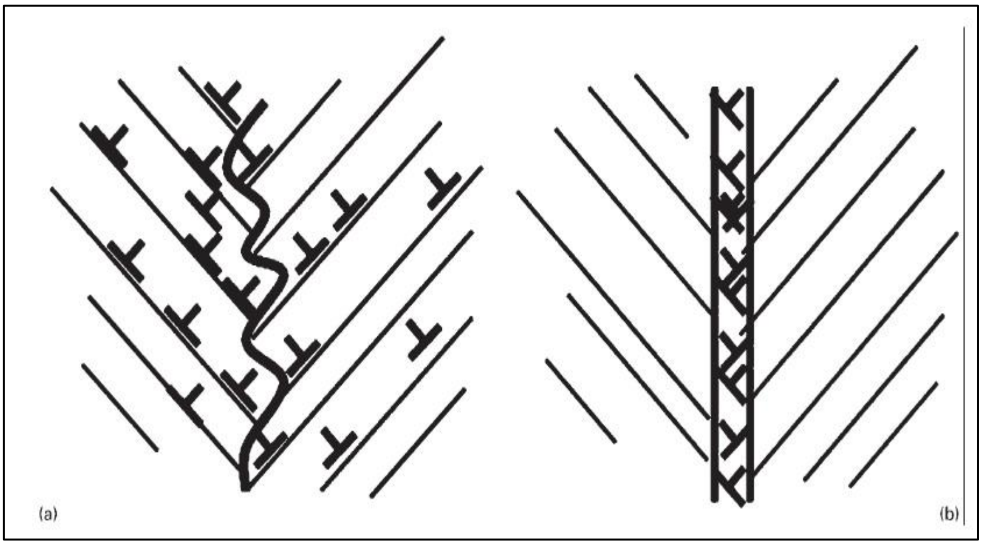


Figure 0.8 [10] – Arrangement of grain boundaries in nanostructured layers

(a) dislocation structure during SPD processing; (b) dislocation structure after SPD processing leading to formation of nonequilibrium grain boundaries [10]

It was shown by recent studies that different shot peening processes can produce nanostructured layers with specific characteristics, regarding microstructural properties and the depth and the dimension of the crystals. Therefore, special attention has been given to shot peening recently. Researches approved and justified this special attention given to shot peening: shot peening is capable to enhance the mechanical behavior and properties of materials under a wide range of load conditions. Moreover, the simplicity of implementation of shot peening in the industrial and commercial scale, makes an attraction when high productivity of nano crystal layers is required. [28] [29]

1.6 Different methods of shot peening aimed at grain refinement

Different shot peening methods exist which have been experimented and used to obtain nanocrystalline surfaces. They are mainly different regarding their technology and the apparatus; also, the results they create on the workpiece. A brief explanation of the latest and most effective methods in this regard will be presented below:

1.6.1 Ultrasonic shot peening method

In ultrasonic shot peening [30] [31] [32]method (also named surface mechanical attrition treatment or SMAT), an ultrasonic transducer produces vibrations that oscillate the shots. A vibration generator produces ultrasonic vibrations inside an enclosed chamber, vibrating multiple steel balls with smooth surface placed inside of it. The vibration frequency of the chamber is usually between 50 Hz and 20 kHz. When the balls are typically of 1–10 mm in diameter. They can be made of different materials. By resonating the shots, the workpiece gets multiple impacts by large number of flying shots over a short period. The directions by which the shots hit the workpiece are rather random. The reason for this is that the shots inside the vibration chamber have accidental flying directions. Consequently, repeated multidirectional hits at immense strain rates onto the sample surface produce severe plastic deformations. This refines the grain size gradually down to the nanometer regime in the surface layer of the workpiece. [32] [33]

Ultrasonic shot peening has been experienced on a wide range of material types giving satisfying results. These include pure steels, alloys and pure metals whose nanostructure structure have been measured up to 50 mm deep from the surface. [34] Obviously, this results the material to perform much better and have improved mechanical properties. [35] [36] [37] [38] [10]

1.6.2 High energy shot peening method

High energy shot peening is a method of shot peening capable of producing nanostructured structure in the surface of the material. [39] Like the other shot peening methods, the surface of the workpiece is entirely bombarded by flying shots with high kinetic energy. This results in the production of a nanocrystal layer on the surface of the workpiece. The working principals of this method are very similar to that of ultrasonic shot peening. However, in high energy shot peening the frequency is usually lower and the shots have bigger diameters. [39]

1.6.3 Surface nanocrystallization and hardening method

Surface nanocrystallization and hardening process is another shot peening method using ultrasonic frequency vibrations to generate nanocrystal layer on the surface of the workpiece. Alike previous methods, this one can produce compressive residual stress in the surface of the workpiece, generate work hardened surfaces and also nanocrystalline structure. [40] [41]

The mechanical devices used in surface nonocrystallization and hardening method are different from that of other shot peening methods. In surface nanocrystallization and hardening method the workpiece is fixed at one end of a cylindrical container which is commonly made of hardened steel. The disc is held in place via mechanical locking by pushing the disc against the rigid cover of the container. Consequently, one side of the disc will be randomly impacted by high speed shots, while the other side of it is held rigidly against the thick cover of the chamber. In this method, usually tungsten carbide/cobalt (WC/Co) are used. The shots have commonly bigger diameters compared to other shot peening methods, and they are loaded into the chamber to create the desired effect on the surface of the workpiece. Before performing the shot peening treatment, Ar gas is used to fill the chamber. By using a Spex 8000 mill, the shots acquire a high speed inside the chamber by shacking it in a three-dimensional movement. The kinetic energy of the balls, which fly having a complex and random pattern of movement, is produced by this three-dimensional shaking. [42] [43] [44] [45] [46]

1.6.4. Severe shot peening

As discussed before, air blast shot peening is a conventional and popular shot peening method, which is widely used in the industrial field due to its simplicity. To change the microstructure in the surface of the workpiece into ultra-fine grains (nanostructure) by using air blast shot peening, one can simply apply specific combinations of process parameters to increase the speed and kinetic energy of the shot impacts or to increase the coverage. [47] [48] Rather than air blast shot peening, the process implemented in this way is named severe shot peening. By using this naming, more emphasis on the micro-structural refinement is given to the process. [49] [50] [51] [52]

2. Ultrasonic shot peening

2.1 What is Ultrasonic Shot Peening

Ultrasonic shot peening (USP) is a mechanical surface treatment method. It improves and enhances the mechanical strength, the fatigue life span, and the corrosion cracking resistance of metallic material parts. These components can have very complex shapes. In the industrial field, these may include compressor impellers, bladed disks, nuclear power plants' pressure vessels, gears, complex automotive parts, etc. In ultrasonic shot peening with help of an ultrasonic vibrator (sometimes called sonotrode), shots in shape of spheres are impacted onto the surface of a workpiece, at high speeds up to 20 m/s. sonotrode (or ultrasonic probe) is the part of an acoustic system that vibrates at ultrasonic frequencies. The shots, the sonotrode and the workpiece are placed inside a chamber called peening chamber. In the industrial field, it is common to customize the peening chamber, and design it based on the specific shape and dimension of the component that needs to be shot peened. [53]

Thus, the shape of the chamber may vary from a very simple cylinder or box for plane or rod form samples in the laboratories, to very complex shapes, which may be a three-dimensional projection of a complex mechanical component.

The peening chamber keeps the workpiece in place and contains the flying balls, causing multiple complex impacts between the shots and the rest of the peening components, being the sonotrode, the chamber and the part. [53]

There are multiple parameters that affect the efficiency of ultrasonic shot peening. Some of these include the duration of treatment, the number and diameter of shots, the geometry of the chamber, the amplitude and frequency of the vibrations, etc.

The major difference between ultrasonic shot peening and traditional shot peening method is the shot size, which is larger in the former. [54]

In Figures 2.1 [32] and 2.2 [55] the schematic set-up of two ultrasonic shot peening devices in action are illustrated.

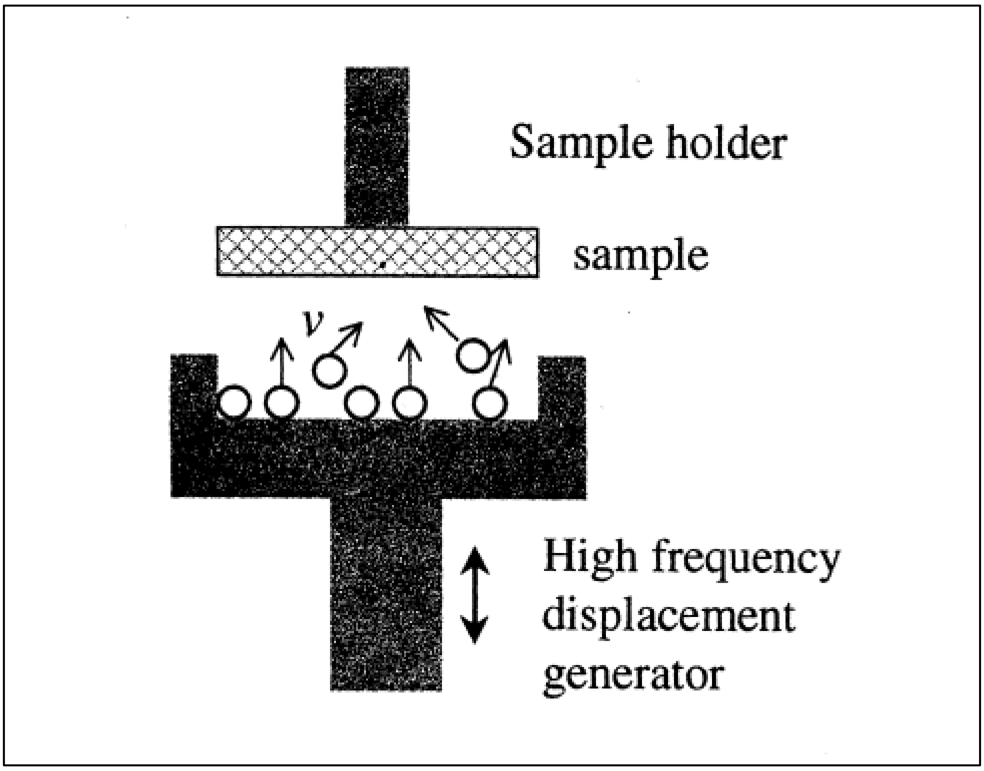


Figure 0.1 [32] – Schematic illustration of the ultrasonic shot peening set-up

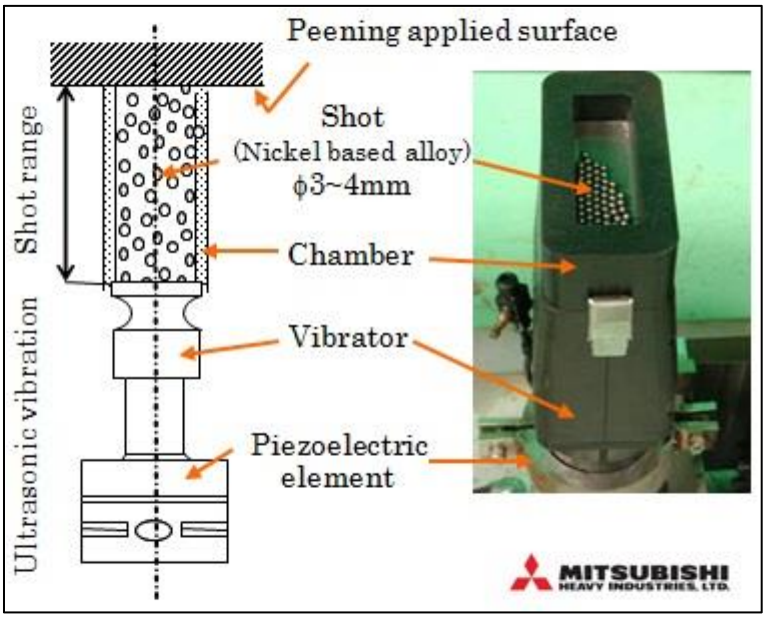


Figure 0.2 [55] – Ultrasonic shot peening Mitsubishi set-up

2.2 A brief history on ultrasonic shot peening

The year 1994 has seen the development of new group of methods for surface plastic deformation, whose purpose was to generate nanocrystal surface layers in materials. J. Lu and K. Lu were pioneers of these methods. In these methods, severe plastic deformation was imposed on the surface of the workpiece either by high velocity shots impacting them, or by peening them with hammer (hammer peening), by surface rolling, machining, or laser shock treatment in order to generate a nanocrystal surface. [32] What was common among all these methods was that they all produced severe plastic deformation on the surface of the workpiece. Among these methods, extra attention was given to ultrasonic shot peening and high energy shot peening since they could treat parts having complex geometries. [56]

SONATS (Stressonic® technology) company developed ultrasonic shot peening method in industrial scale, [53] and since then onwards, this process is witnessing widespread usage and outstanding advances in the industrial field.

2.3 Applications of ultrasonic shot peening

Ultrasonic shot peening is widely used both in the research and industrial fields. In the field of research, its main application has been to study the nanocrystalization the surface of materials.

Metal fatigue, a destructive phenomenon for mechanical parts under dynamic loadings, is one of the most important factors initiating cracks and consequently failure to them leading to an increase in the maintenance and reparation costs and decrease in the life span of mechanical components. That is why ultrasonic shot peening, as an effective, economical, fast and flexible process of increasing the fatigue resistance of complex mechanical parts, has the potential to be widely used in various industrial fields.

To name some major industrial fields in which ultrasonic shot peening process is gradually finding application on several end-markets for treatment of critical mechanical parts we can mention:

Aerospace (engines, turbines, aero-structures, and equipment), naval, energy (power generation), tooling, automotive, medical, materials, heavy industry (mining and oil & gas), rail industry, infrastructures (transportation, industrial), Among the metal materials who have been successfully treated by use of ultrasonic shot peening, iron, titanium, aluminum, nickel base alloys (Inconel), carbon steel, steel, inox, bronze alloys, high strength steels, etc. can be mentioned. [57]

2.4 A brief introduction on the working mechanism of ultrasonic shot peening devices

As discussed before, in ultrasonic shot peening spherical shots are placed in a reflecting chamber (including an ultrasonic concentrator) whose vibrating motion is produced by an ultrasonic generator, causing the shots to resonate. The system, having high frequencies (commonly between 20 and 50 kHz), can treat the surface of the workpiece, peening it with multiple impacts in a short time span. [32]

The main parts of a typical ultrasonic shot peening apparatus produced by Sonats Company are illustrated in Figure 2.3 [58]. As described by the producer: [58]

The generator has the role to create digital sine waves with having frequencies in the range of ultrasound.

Then this electrical signal is converted to mechanical signal, by help of a Piezo-electrical emitter.

A set, consisting of some boosters and an ultrasonic probe (also called sonotrode in the industry), then amplifies this mechanical signal and by transmitting it to the shots, causes them to be thrown to the surface of the workpiece.

Thus, there is no transmission of the ultrasonic waves and vibrations to the workpiece.

The range of the amplitude of vibration of the ultrasonic probe may differ from 10 up to 250μm.

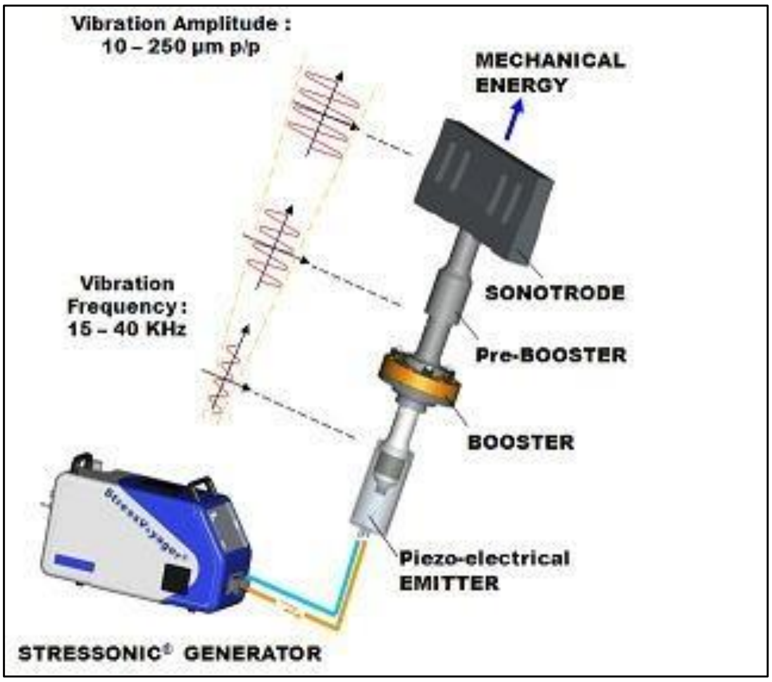


Figure 2.3 [58] – main parts of a typical ultrasonic shot peening device made by Sonats Company

2.5 How ultrasonic shot peening affects the surface of the material

For further development of the ultrasonic shot peening technology, it would be advantageous to understand the formation process of nanocrystallites during the shot peening process. As discussed before, in ultrasonic shot peening the shots impact the surface of the workpiece with high velocities and in a random pattern. This leads to formation of a gradient variation of strain and strain rates from the top surface of the workpiece (where the amount of both is large) to the deep matrix (where their amount reaches zero). Figure 2.4 presents a schematic illustration of this phenomenon, where the grain size changes gradually from a few nanometers in the top surface to micrometers. [59]

Experiments by J. Lu and K. Lu on various materials show that the thickness of the nanostructured surface layer (with grain size of various dimensions from few nanometers on top to 100 nm in the inferior part) can reach up to 50 µm. Under this layer, a refined structured layer (up to 100 µm thick) can be found in which sub-micrometer-sized crystallites or cells are separated by either grain boundaries or sub-boundaries. Below this layer, a layer consisting coarse and deformed grains can be found having different dislocation configurations (these include dense dislocation walls, dislocation tangles, and dislocation cells). A schematic illustration of these layers can be seen in Figure 2.4. The thickness of each of these layers may vary depending on the material of the workpiece and on the process parameters including shot size, frequency of the vibration, etc. [59]

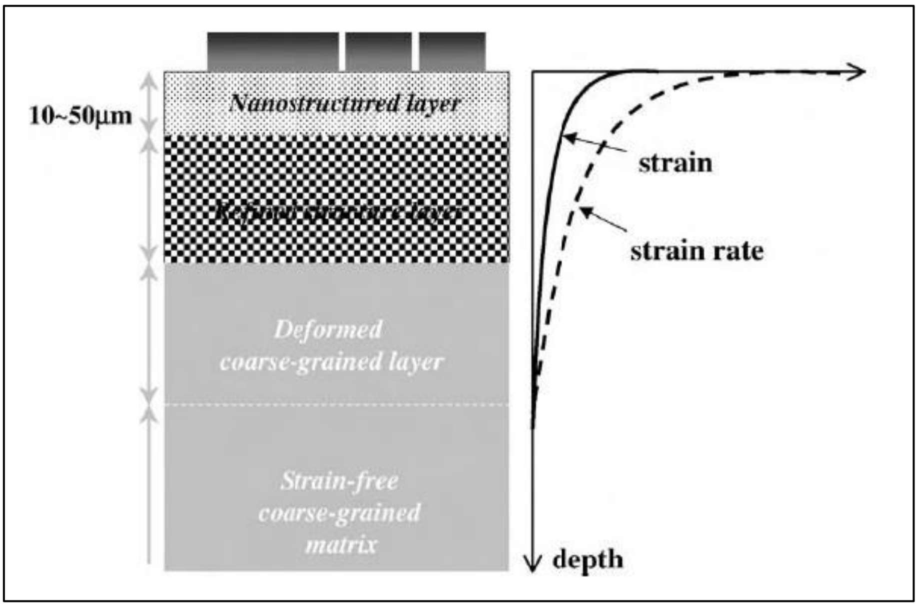


Figure 2.4 [59] – Schematic view of different surface layers (according grain size) generated on the workpiece after ultrasonic shot peening

The nanostructure formation process by ultrasonic shot peening which changes poly-crystals with coarse grains in the surface of the workpiece, is achieved by various dislocations and grain boundary developments. In metals, plastic deformation action and dislocation activities is heavily reliant on the structure of the lattice of the metal and its stacking fault energy (SFE). As an example, in materials having low SFEs, the modality of plastic deformation may change from dislocation slip to mechanical twins (especially under high strain rate), while in materials having high SFEs, dislocation walls and cells, formed to accumulate strains and sub-boundaries, are generated to subdivide coarse grains. [60]

For a better understanding of the procedure, K. Lu and J. Lu took three typical material types each having different lattice structures and SFEs to observe the surface nanocrystallization process via the ultrasonic shot peening process. Detailed observation of each sample by using transmission electron microscopy (TEM) showed that each of these material types undergoes a different grain refinement procedure, causing them to have different specifications which are briefly explained below: [59]

a) For Fe sample (having a bcc structure with a high SFE) the thickness of the nanograin layer has been reported as 60 µm and the nano-crystallization process has been as followed:
   (1) Development of dense dislocation walls (DDWs) and dislocation tangles (DTs)
   (2) Transformation of DDWs and DTs into subboundaries with small misorientations
   (3) Evolution of subboundaries to highly-misoriented grain boundaries

b) For Cu sample (having an fcc structure with a medium SFE) the thickness of the nanograin layer has been reported as 35 µm and the nanocrystallization process has been as followed:
   (1) Development of equiaxed dislocation cells (DCs)
   (2) Formation of twins and subboundaries with small misorientations
   (3) Evolution of subboundaries to highly-misoriented grain boundaries

c) For AISI 304 stainless steel sample (having an fcc austenite structure with a very low SFE) the nanocrystallization process has been as followed:
   (1) Formation of planar dislocation arrays and twins
   (2) Grain subdivision by twins and martensite transformation
   (3) Formation of nanocrystallites

2.6 Parameters affecting the result on the workpiece

In ultrasonic shot peening the main process parameters affecting the result on the workpiece are the duration of the treatment, the shot diameter, the number of shot, the ultrasonic vibration amplitude and frequency, which are all very easy to control compared to conventional shot peening methods. It is common to use some techniques for controlling the conditions of the shot peening. One of these techniques is the use of the Almen Strip. [32]

The material of the workpiece, sonotrode, chamber and shots, and also the geometry and shape of the chamber are among the factors influencing the final result. [61]

3. Design of ultrasonic shot peening device

3.1 Description of the design approach

As discussed in the previous chapter, the ultrasonic shot peening (USP) device consists of different mechanical and electro-mechanical parts, each of which, based on their specifications, can significantly change the outcome of the process. These parts, which are the main constituting components of any typical USP device, can be categorized in three groups: The peening chamber, the sonotrode, and the shots.

However, in USP, the outcome of the device can also strongly change based on the geometry and material of the treated workpiece. In fact, the consideration of the shape and material of the workpiece in the design of the USP device is of such importance that in the industry, often customized chambers are designed for each workpiece that comes with a different geometry.

Thus, the first step in our design of the USP device was to find out of what material and what geometry our typical sample workpieces would be.

After having known our sample workpieces' specifications, we categorized them into four groups: of which, three needed to be treated at room temperature conditions and one (magnesium sample) needed to be treated at high temperatures. We then realized that we would need two different USP devices with completely different chamber designs to match the required conditions for all our samples: one which works at room temperature (discussed in this chapter), and one which needs to reach high temperatures (discussed for possible future developments in chapter four).

The next step was designing the chamber (and choosing its material), choosing the shots (diameter and material), and choosing the sonotrode (dimensions, material, frequency and amplitude). These were achieved by close study of the literature, study of the relevant industrial products, and finding and considering different parameters influencing the design (or selection) of each component.

We also realized that vacuum conditions are required for both of our USP device designs. The solution for the vacuuming of each device is described in each chapter separately.

Eventually, a three-dimensional CAD design of our USP devices with their constituting components was drawn by help of CATIA software.

In the next sections of this chapter the specifications of our workpieces of interest will be presented, followed by the detailed description of the design and selection of the main components of our USP device working at room temperature conditions.

3.2 Samples to be used at room temperature

3.2.1 Almen strip sample

One of the sample workpieces, which was chosen to be treated by our device was the Almen strip. In section 3.1, detailed description of the Almen strip and its usage are presented. For our design, all three standard types of Almen strip were considered for use. The dimensions of the N type Almen strip are provided in Drawing 3.1. The length and width of the A and C type Almen strip are the same as the N type, but they have a different thickness (1.2954 mm for type A and 2.3876 mm for type C). A three-dimensional rendering of the N-type Almen strip can be seen in Figure 3.1.

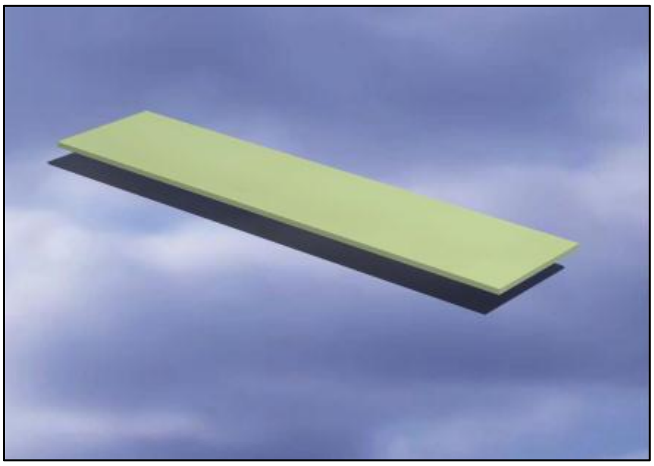


Figure 0.1 – 3D rendering of the N-type Almen strip sample

For the Almen strip, it is also important to respect the standard condition of the holding fixture. The standard condition can be seen in Figure 3.2

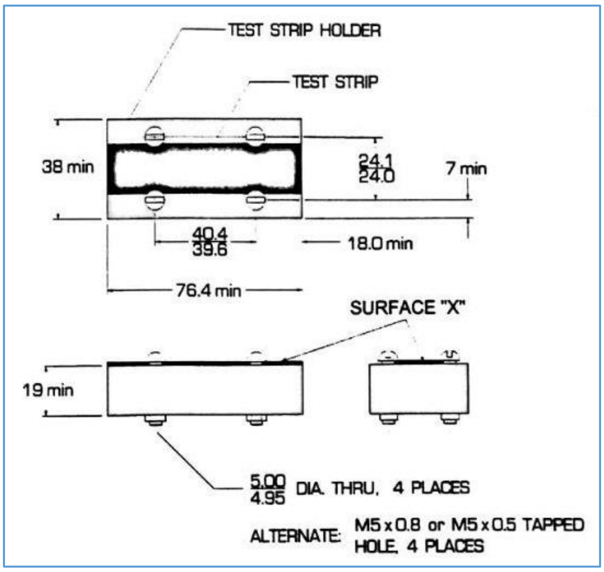


Figure 0.2 [21] – Standard condition for Almen strip holding fixture

3.2.2 ASTM E8/E8M – 09 plate tensile test sample

The other sample to be shot peened by our device is the ASTM E8/E8M – 09 plate tensile test sample (for simplification called E8/E8 sample from here onwards). The dimensions of this sample are given in Drawing 3.1. With this sample, it is important to consider that all the reduced section of the part, needs to be inside the peening chamber. The standard defines different geometries for this samples as they can have different thicknesses, whose maximum is 6 mm. A three-dimensional rendering of this sample can be seen in Figure 3.3.

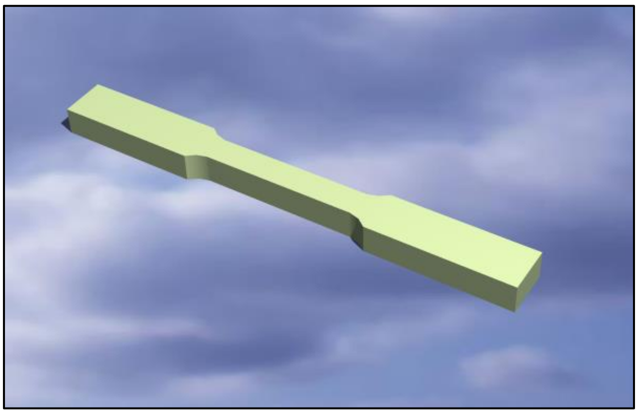


Figure 3.3 – 3D rendering of ASTM E8/E8M – 09 sample

3.2.3 ASTM E466-15 rod-shaped tensile test sample

Our last sample of interest to be shot peened at room temperature is the ASTM E466-15 rod sample. The dimensions of this sample are given in Drawing 3.1. For this sample, like the ASTM E8/E8M – 09 sample, it should be considered that all the reduced section of the part needs to be inside the peening chamber. Another important feature to be considered in our design for this sample is that it needs to be rotated at a constant speed while being shot peened. The E466-15 rod can have different diameters, whose maximum is 16 mm. For the 3D design, we considered the case with the maximum diameter, although our design also considers the availability of installation of samples with smaller diameters (will be discussed in the following chapters). A three-dimensional rendering of this sample can be seen in Figure 3.4.

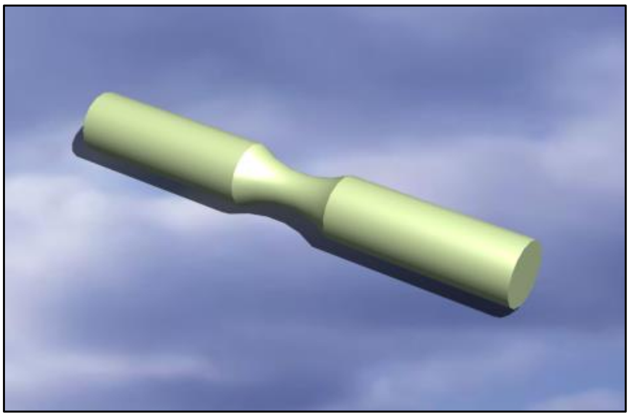
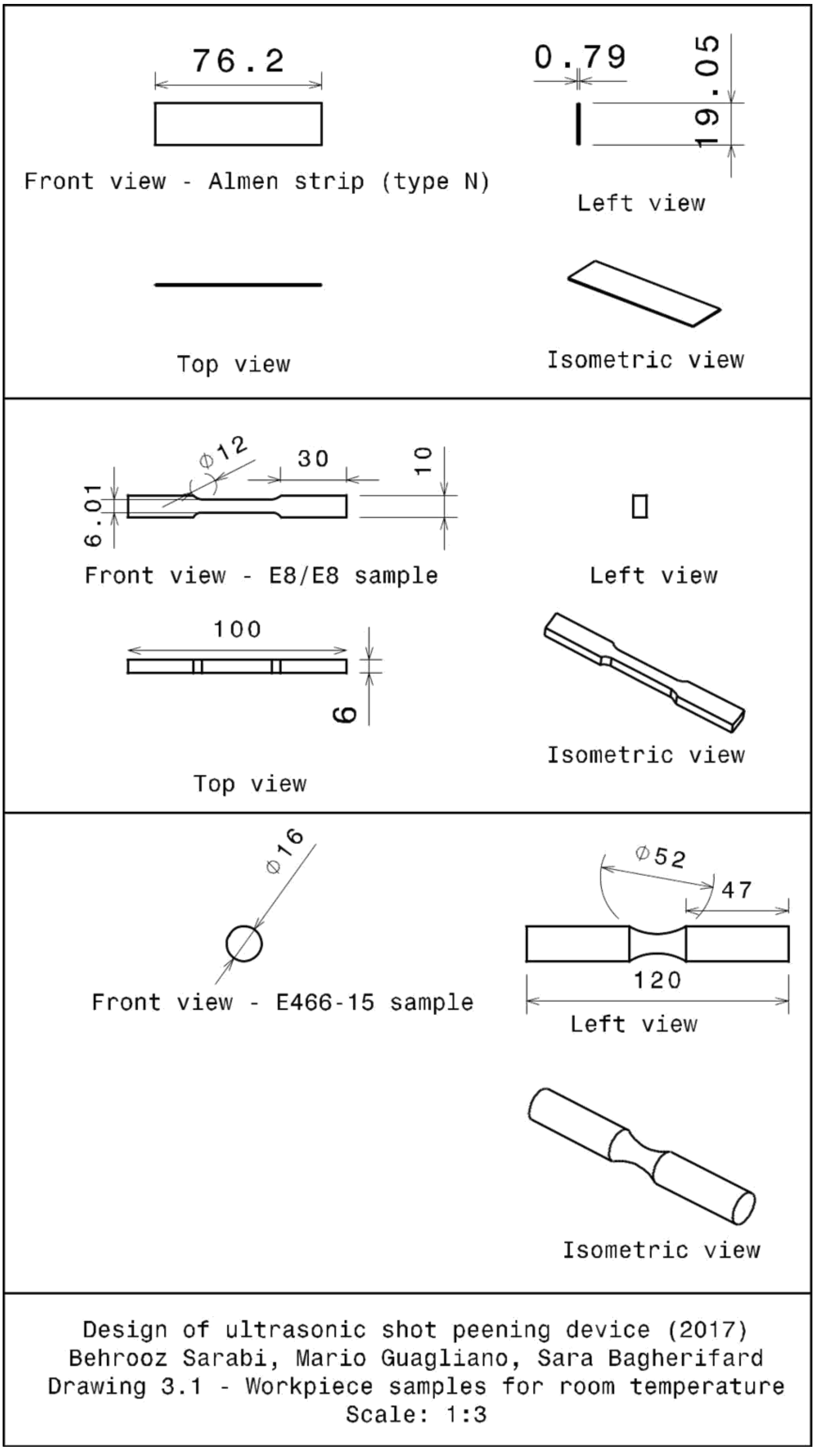


Figure 0.4 – 3D rendering of ASTM E466-15 rod sample



Drawing 0.1 – Workpiece samples for treatment in room temperature

3.3 Chamber design

3.3.1 Chamber material selection

The choice of the material of the chamber is of high importance. This is due to the fact that the chamber is constantly being impacted by shots during usage of the device, which makes it vulnerable to deformation, wear, and other modes of mechanical failure.

Different materials were found to be used for the chamber in the literature and in the industry. These include hardened steel, aluminum, steel, polycarbonate, ALS (aluminium covered with a polymer adhesive strip) and polymerics (POM or Polyoxymethylene).

In USP, an important factor that needs to be considered for material selection is the Restitution Coefficient (R.C). [62] It is defined as the ratio of the final to initial velocity difference between two objects after their collision. This coefficient ranges from 0 to 1, where 1 would be defined as a perfectly elastic collision.

We chose hardened steel (which has a relatively high R.C when hit by steel shots; Considered 0.8 by M. Zarwel et al. [63]) as the material for our chamber for the following reasons:

- Studies show that doubling the R.C causes the impact velocity and impact density (distribution of number of impacts per mm^2) of the shots to be almost doubled, and the impact depths on the workpiece to increase. [63] These effects are desirable regarding the treatment.
- Experiments comparing different materials for the chamber also showed that increasing R.C leads to an increase in the number of impacts and the homogeneity of the impacts. [62] [64]
- Hardened steel has a higher R.C. compared to other sets of materials used in the literature and also has adequate mechanical strength. It is widely used both in the literature and in the industry for similar applications.

In Table 3.1, which is a summarization of our research on choice of chamber material, the influencing parameters, different materials used in the literature, and justification of our choice are presented.

Chosen material	Remarks	Other materials used in articles	Justification of chosen material based on remarks/statistics
hardened steel	Doubling the Restitution Coef. (R.C) causes the impact velocity and impact density to be almost doubled; also, increases the impact depths. [63]	aluminum [65] [66] [62] [67]	• It was used more often in real (not computer aided simulation) experiments. • Higher R.C. gives higher homogeneity, higher number of impacts, higher impact depths and higher impact velocity.
	Increasing R.C leads to increase in impacts; also, increases homogeneity of impacts. [62] [64]	Steel [53]	
		Polycarbonate [64]	
		ALS (AL covered with a polymer adhesive strip) [62]	
		polymeric (POM or Polyoxymethylene) [63]	

Table 0.1 – Chamber: material selection

3.3.2 Chamber preliminary shape and dimensions selection

The first step in designing the shape of our chamber was to study closely the literature to find influencing parameters.

Due to the simplicity of the geometry of our sample workpieces (simple plate and a simple rod), we realized that the main body of our chamber could be of a simple shape. Thus, as our preliminary shape-design, we considered two simple choices: a box-shaped chamber or a cylinder-shaped chamber. It is worth to note that these shapes were both widely used in the literature for plate- and rod-formed sample workpieces.

Between these two shapes, we eventually chose the box shape, considering the following parameters:

- There is not much difference in number of occurring impacts between a cylinder- and a box-shaped chamber with the same volume. [65]

- The box shape is most commonly used in articles with rod-shaped samples.
- The box-shaped chamber is easier to produce than cylinder-shaped one (especially considering its holes and fittings, and ball bearing installation which are explained in next section).

As for the dimension, this was our preliminary selection: 40*62*62 [mm] (height*width*length). The reasons for this selection were:

- These dimensions are closest to the dimensions available in the literature (with working conditions similar to ours).
- The smaller the dimension of the chamber, the higher would be the impact velocity. [64]
- J. Badreddine et.al did a close study on the shape and dimensions of the chamber and also measured the influence of different USP parameters (including shot size, frequency and amplitude of sonotrode, etc.) simultaneously. Their experiments were performed by using a chamber with this volume (40*62*62 [mm]) [65]. Keeping our chamber's dimensions within this range would help us take advantage of the data obtained by Badreddine et.al.

However, these dimensions were not big enough to fit our Almen strip entirely in the chamber (as required by the standard). This led us to increase the dimensions of our chamber to 40*74*74 [mm] (height*width*width), which is slightly bigger than our first choice.

In Table 3.2, which is a summarization of our research on chamber shape and design, the influencing parameters and justification of our choices for the shape and dimensions are presented.

There was no information available in the literature regarding the thickness of the chamber. We suggested 16 mm for the body thickness of the chamber.

Chosen shape	Chosen inside dimensions (h*w*l)	Remarks	Justification of chosen shape based on remarks/statistics	Justification of dimensions based on remarks/statistics
Box	40*74*74 [mm]	There is not much difference in number of occurring impacts between a cylinder- and a box-shaped chamber with the same volume. [65]	• There is not much difference in number of impacts between a cylinder- and a box-shaped chamber with the same volume. • The box shape is most commonly used in articles with rod-shaped samples. • The box shaped sample is easier to produce than cylinder shape one. (especially considering the wholes and fittings and bearing installation which is explained in next section)	Since we need to fit in the Almen strip, this dimension was the closest possible to accord with the dimensions commonly used in literature. (Smaller volume of the chamber givers higher impact speed).
		At edges, there is less impact velocity and homogeneity, but the number of impacts are slightly higher. [65]		
		At edges with acute angles (considering angles smaller than 90 degrees), there are higher concentration and slightly higher number of impacts, but less homogeneity and impact velocity. [64]		
		The smaller the dimension of the chamber, the higher would be the impact velocity. [64]		

Table 0.2 – Chamber: shape and dimension selection

3.3.3 Modification of the design of the chamber to match all three samples

To be able to treat all 3 workpiece samples with our box-shaped chamber, we needed some modifications in our preliminary design. This was achieved by designing fittings (to hold the weight of the sample, cover the holes, keep the samples in place, and ensure the smoothness and flatness of the inner surface of the chamber) and two different types of lids (one with holes to hold the Almen strip as requested by the standard, and one without holes for the plate and the rod-shaped sample), and also by implementing bearings (for holding/rotating the rod-shaped sample during the treatment).

Also, holes for fixing the auxiliary parts (fittings, screws, bearing, and the lid) were devised in the chamber.

In Figure 3.5 a three-dimensional rendering of the modified chamber is presented.

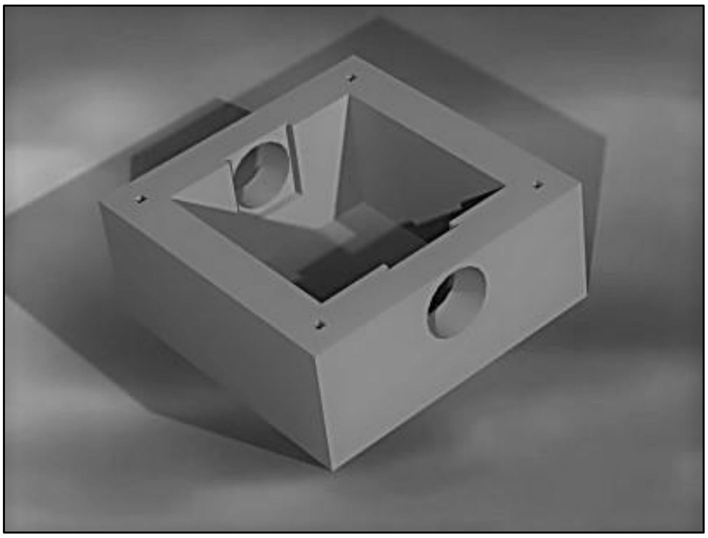


Figure 0.5 – 3D rendering of the modified chamber

To keep the volume of the chamber as small as possible, (as explained previously in section 3.3.2), we designed the Almen strip to be fixed to the lid with a 45-degree angle inclination regarding the edges of the lid. According to the standard (Figure 3.2), M5 tapped screws and nuts were used to fix the Almen strip to the holed lid. A 3D rendering of the Almen strip fixed to the lid can be seen in Figures 3.6. and 3.7. Dimensions of the lids (holed and un-holed), the screws, and the nuts can be found in Drawings 3.3 to 3.6.

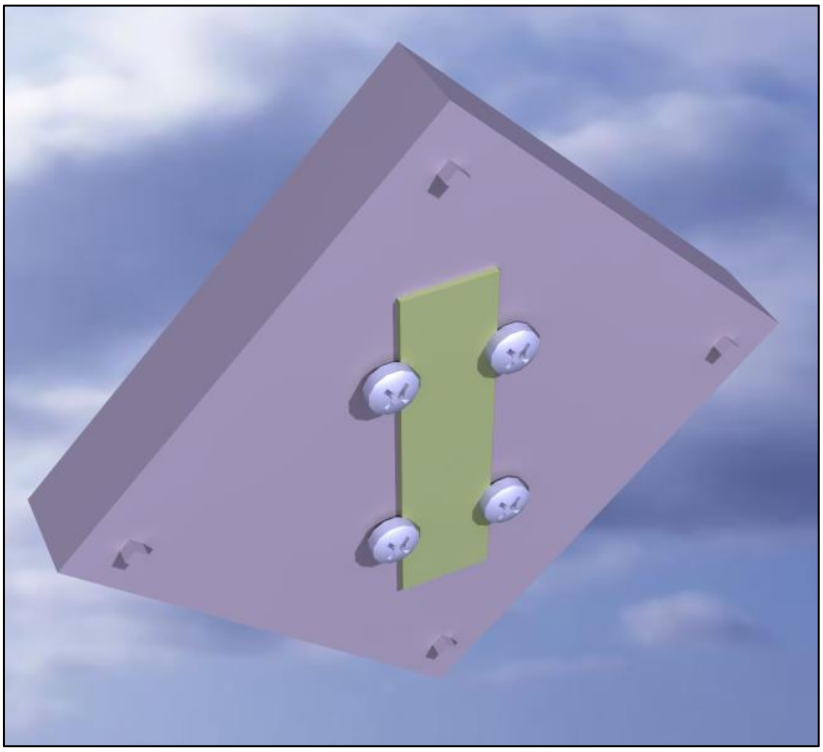


Figure 0.6 – Almen strip fixed to the holed lid (internal view)

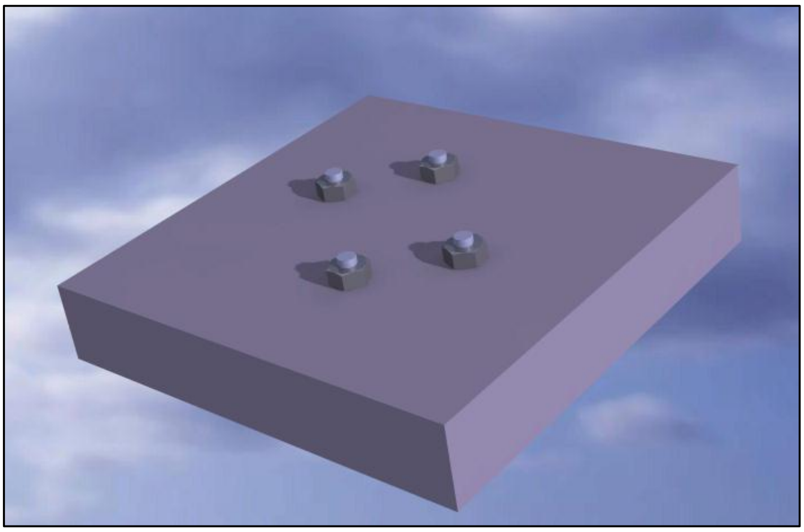
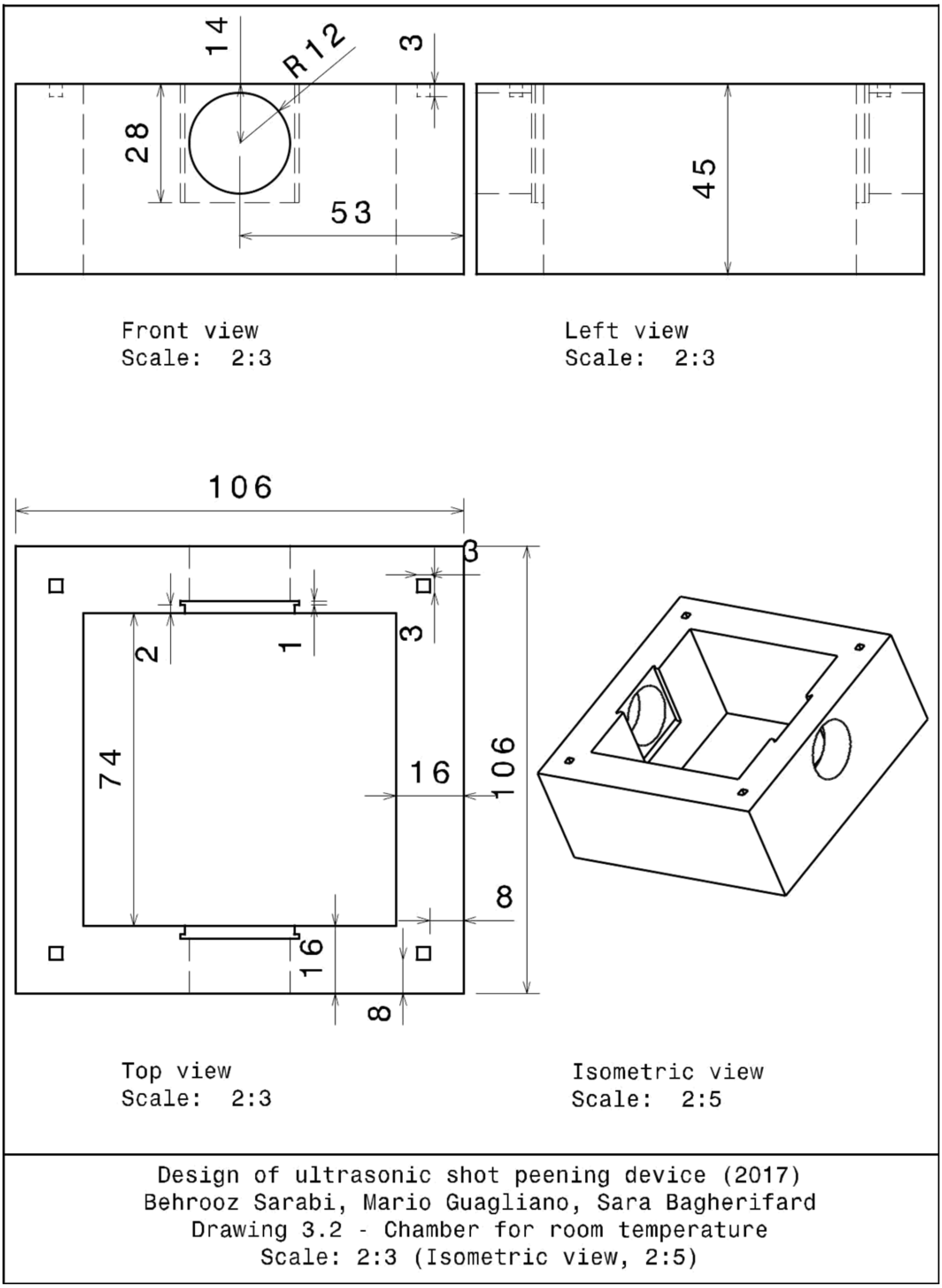
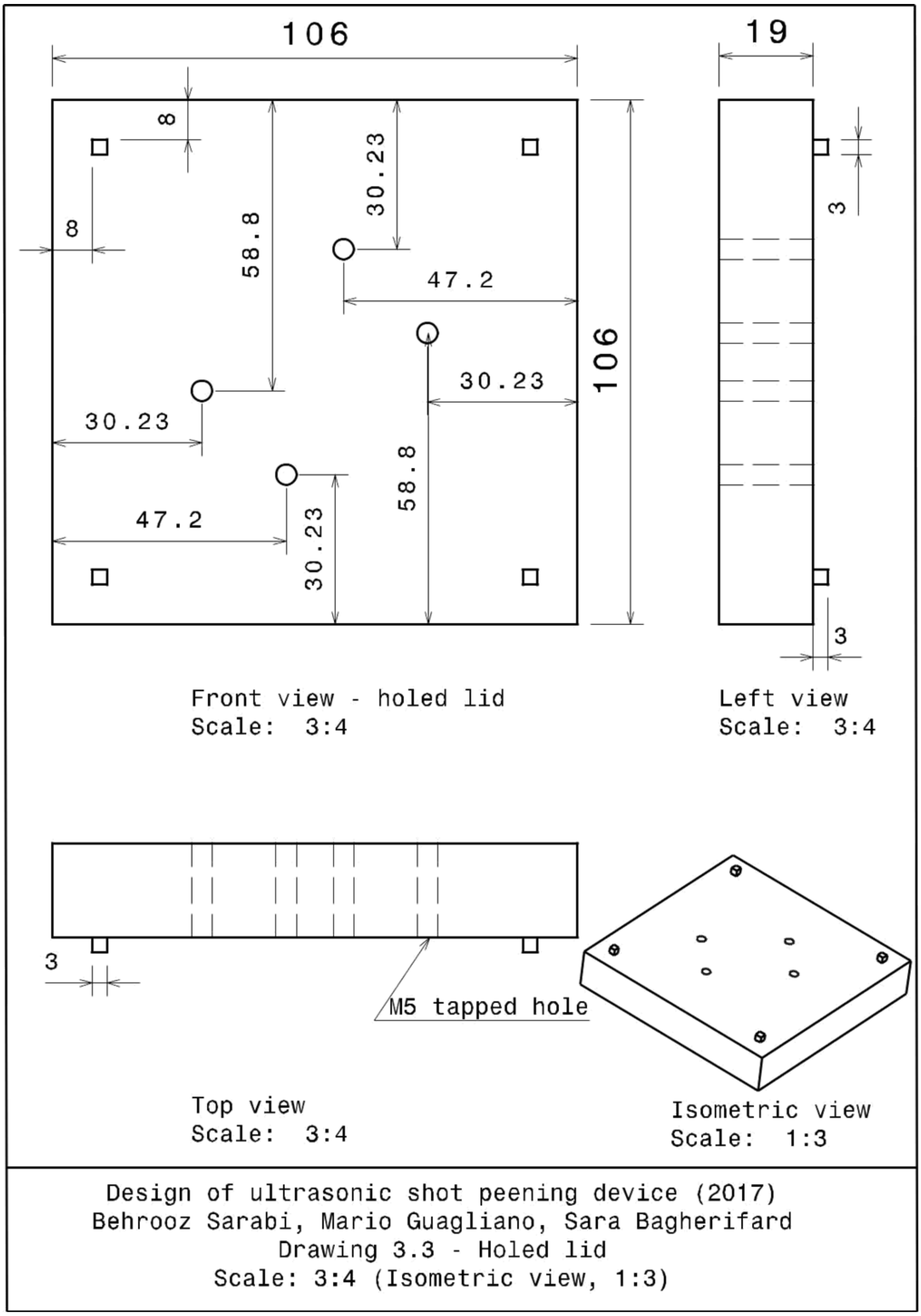


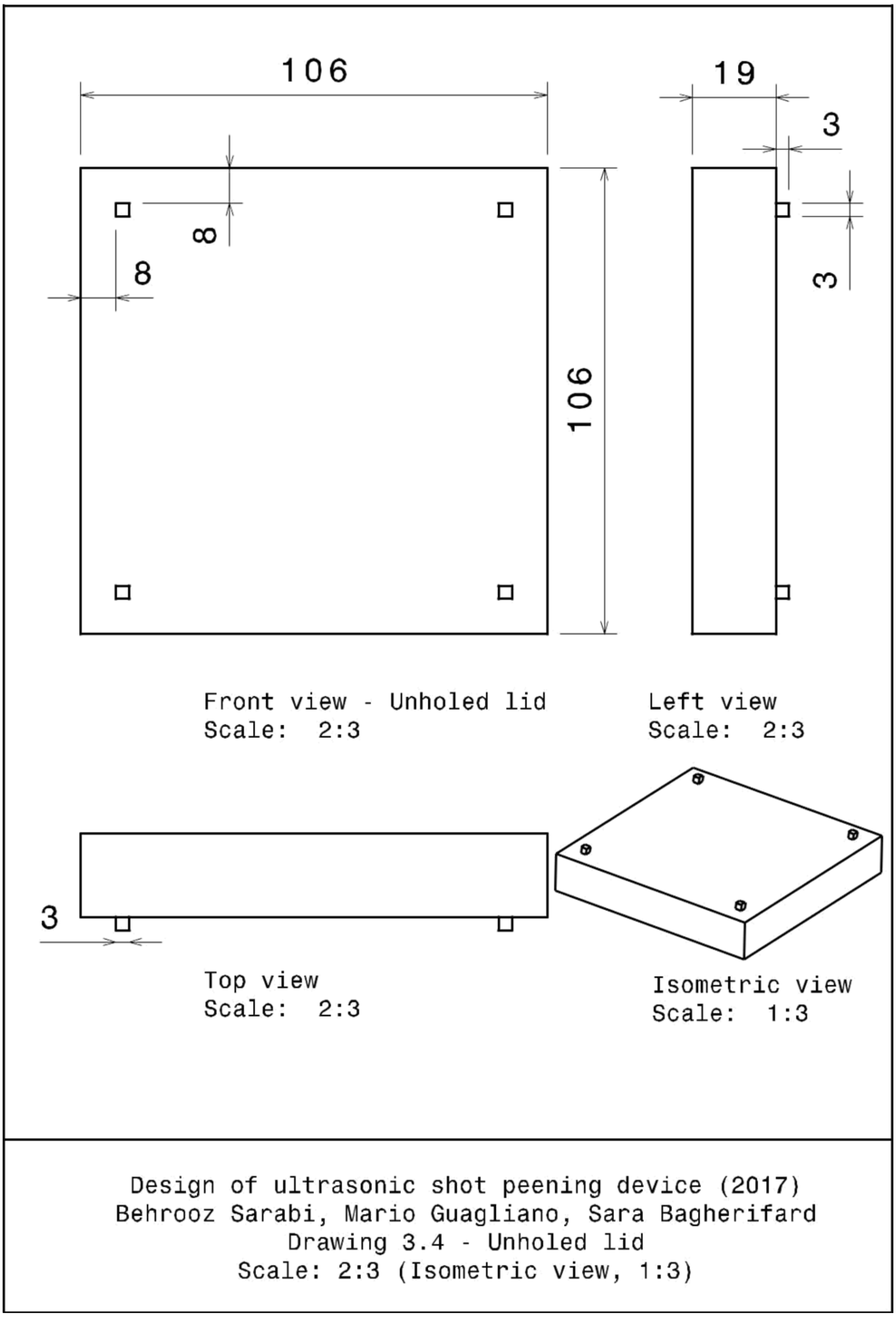
Figure 0.7 – Almen strip fixed to the holed lid (external view)



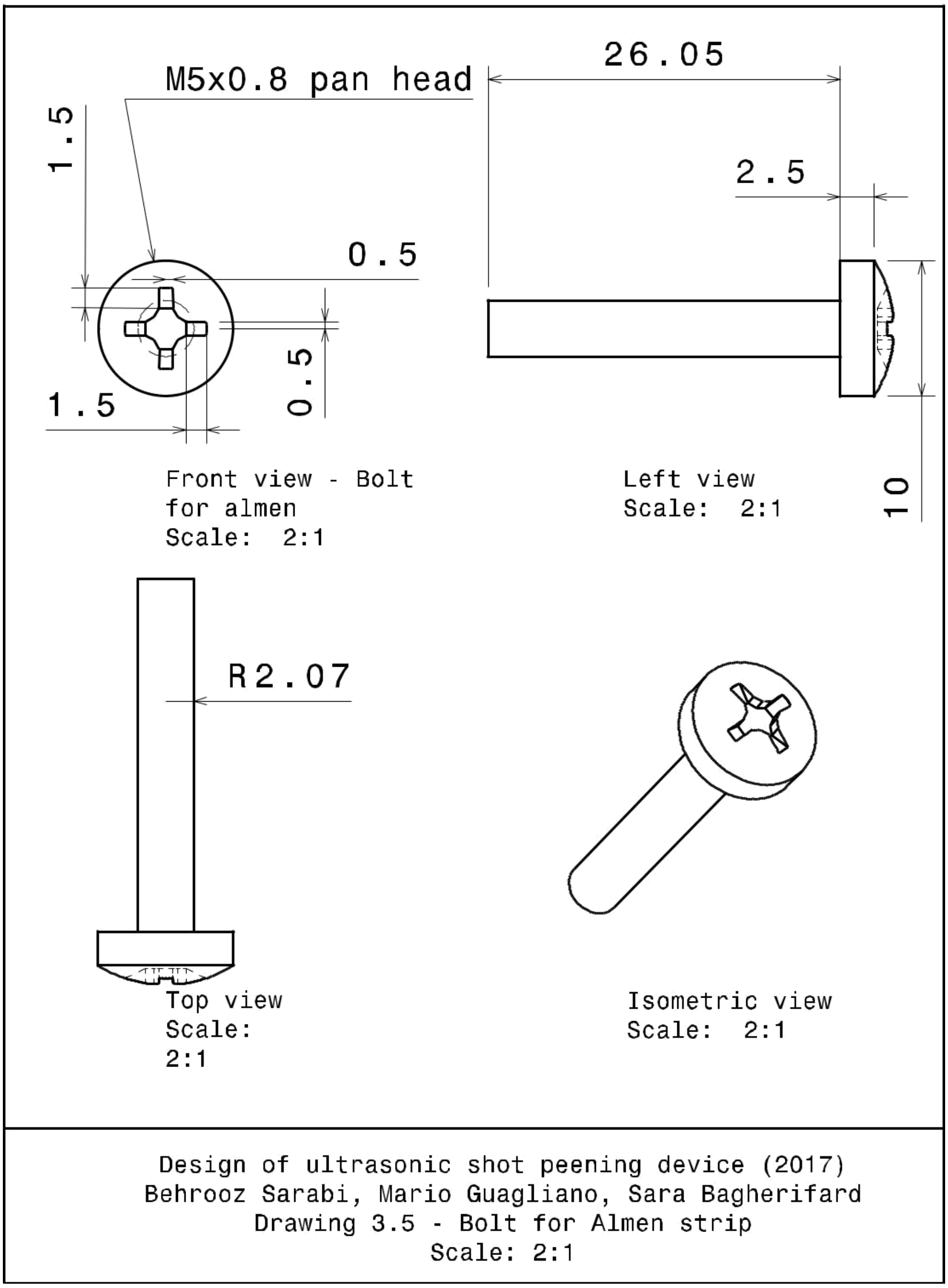
Drawing 0.2 – Chamber for room temperature conditions



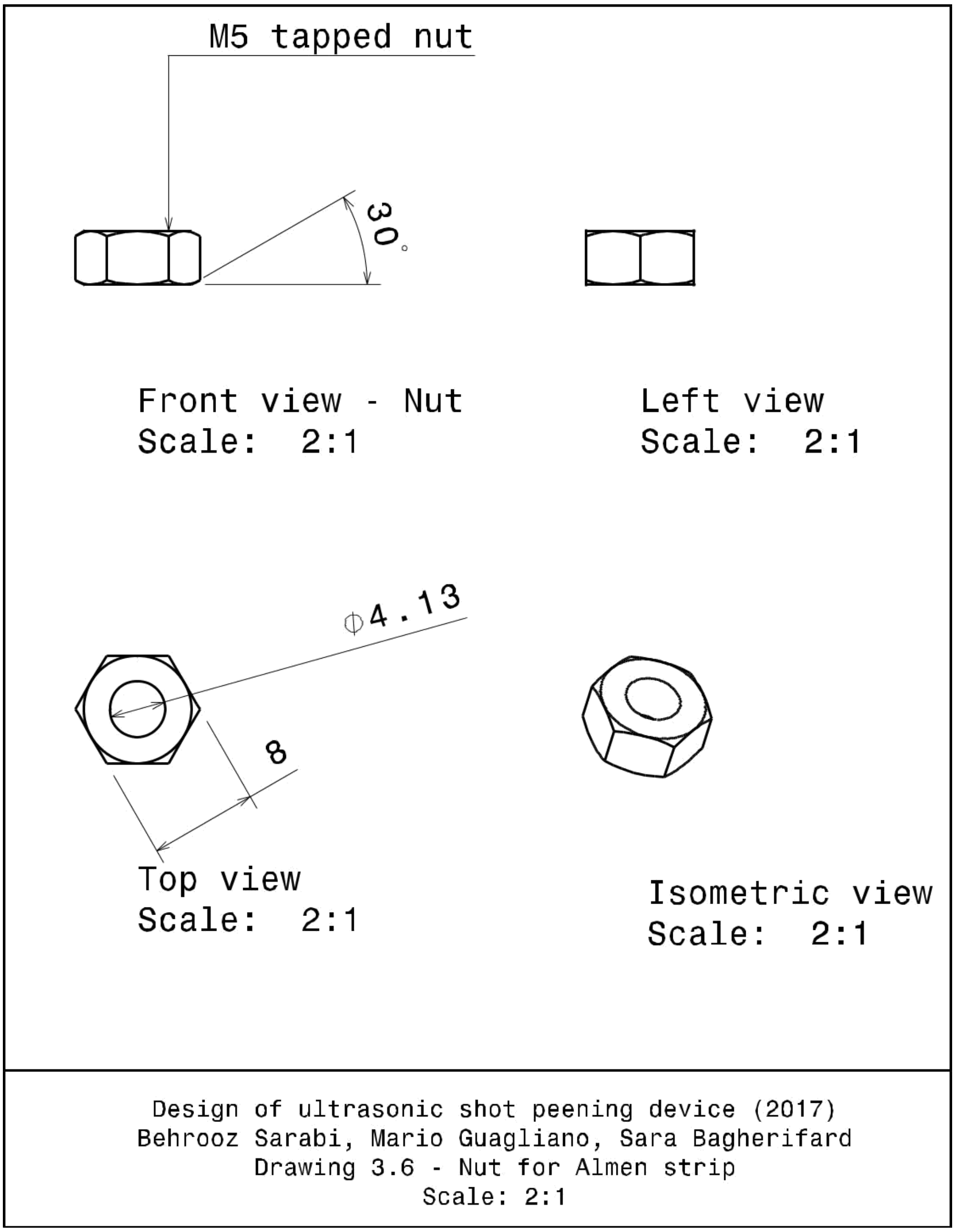
Drawing 0.3 – Holed lid



Drawing 0.4 – Un-holed lid



Drawing 0.5 – Bolt for Almen strip



Drawing 0.6 – Nut for Almen strip

3.3.4 Bearing selection for the chamber

As discussed in section 3.2.3, we need our rod-shaped sample to rotate while being shot peened. To make it possible, we decided to mount bearings in our chamber. For this, we chose a pin bearing with an inner diameter of 16 mm and an outer diameter of 24 mm and with a thickness of 13 mm. To keep with these dimensions, the RNA bearing-series (needle roller bearings) of SKF Company can be used. A three-dimensional rendering of the bearing can be seen in Figure 3.8.

3.3.5 Fittings design for the chamber

As discussed in section 3.3.3, in order to be able to treat all 3 workpiece samples with the same chamber, we needed some modifications in the preliminary design of the chamber. This was achieved by designing special fittings, which serve to:

- hold the weight of the sample,
- cover the holes when they are open,
- fix the samples in place when treated,
- ensuring the smoothness and flatness of the inside surface of the chamber when the holes are to be closed (right?)

The advantage of our design of the fittings is that they are small and not costly to be produced. Thus, many of them with different hole sizes can be produced to match different workpiece samples with different sizes. (In sections 3.2.2. and 3.2.3. it is explained that our workpiece samples can have different thicknesses and diameters).

Thus, each time by simply changing the fittings we can treat any of our 3 type samples.

It is demonstrated in Figure 3.8 how simply by sliding the fittings in place, one can prepare the chamber for shot peening the Almen strip sample (or any other type of our workpiece samples).

A three-dimensional rendering of each of these fitting types in use, can be seen in Figures 3.9 to 3.11.

The dimensions of these fittings are given in Drawing 3.7.

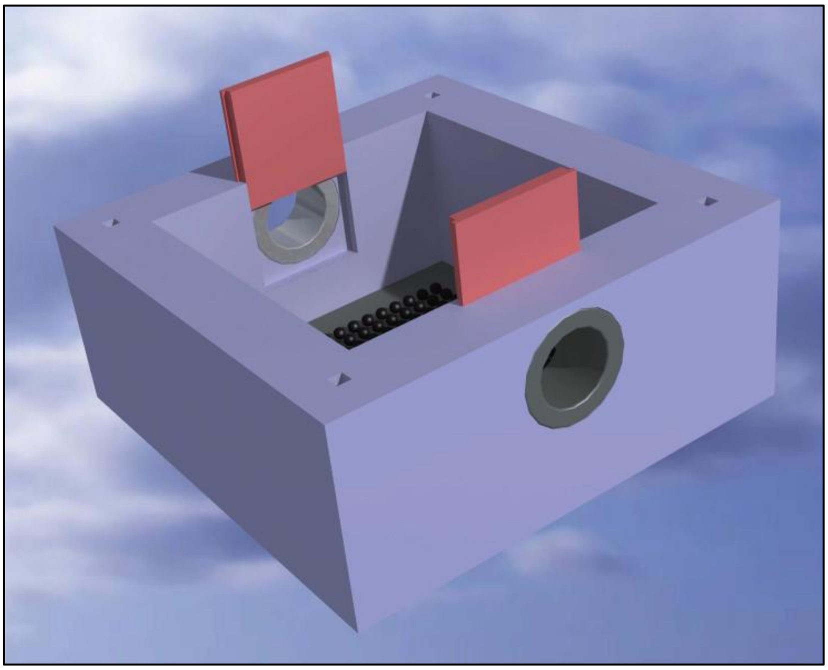


Figure 0.8 – Chamber preparation (sliding appropriate fittings in place) for Almen strip sample treatment

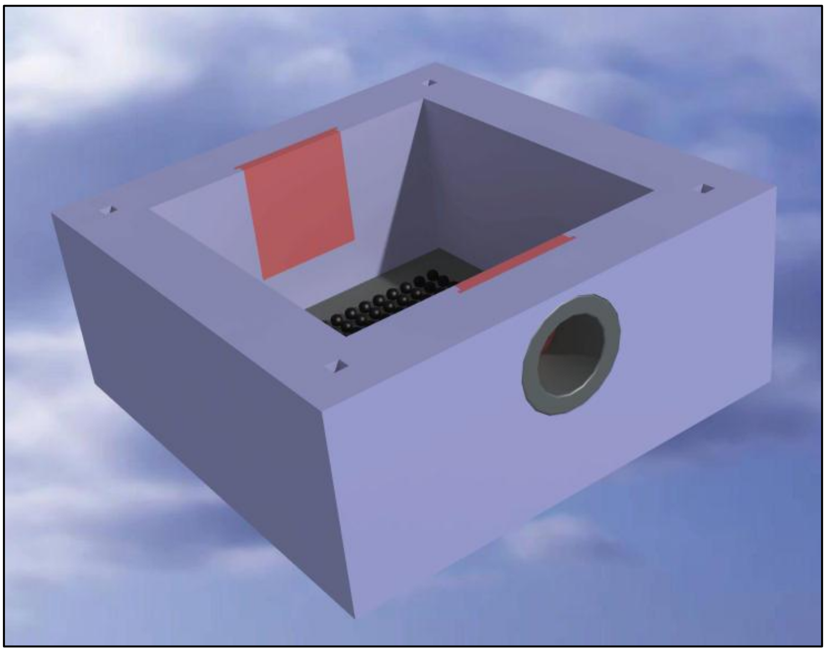


Figure 0.9 – Chamber ready for Almen strip sample treatment

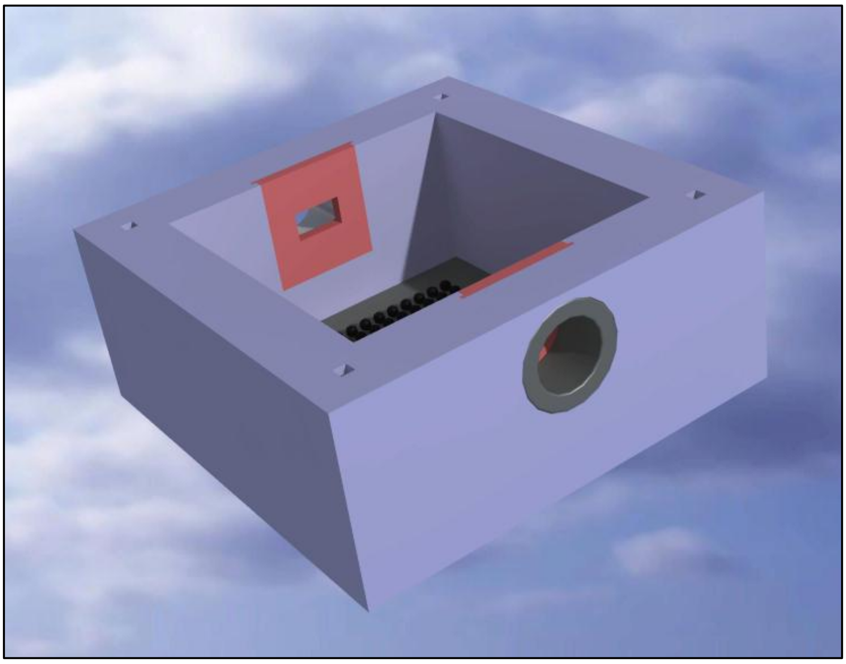


Figure 0.10 – Chamber ready for E8/Æ8 sample treatment

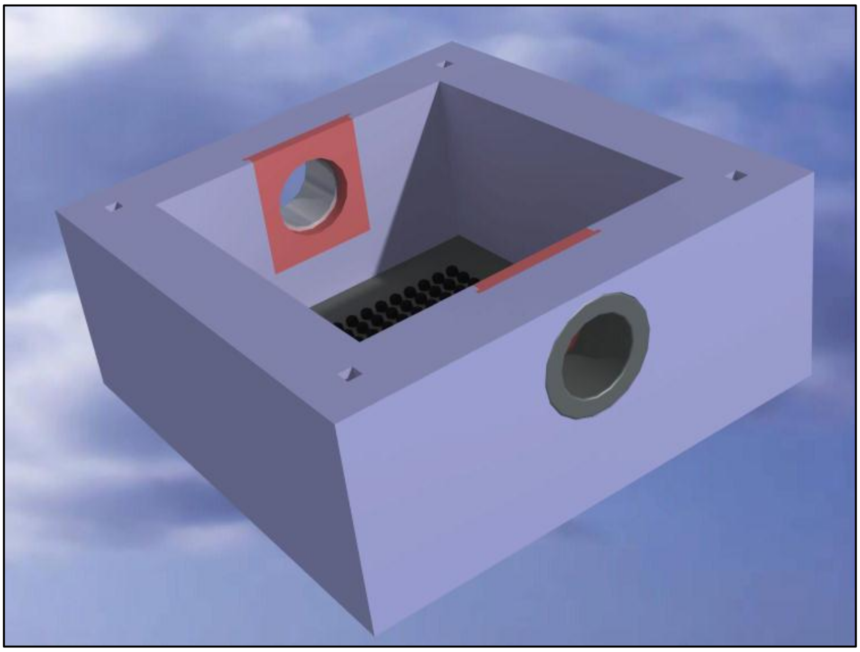
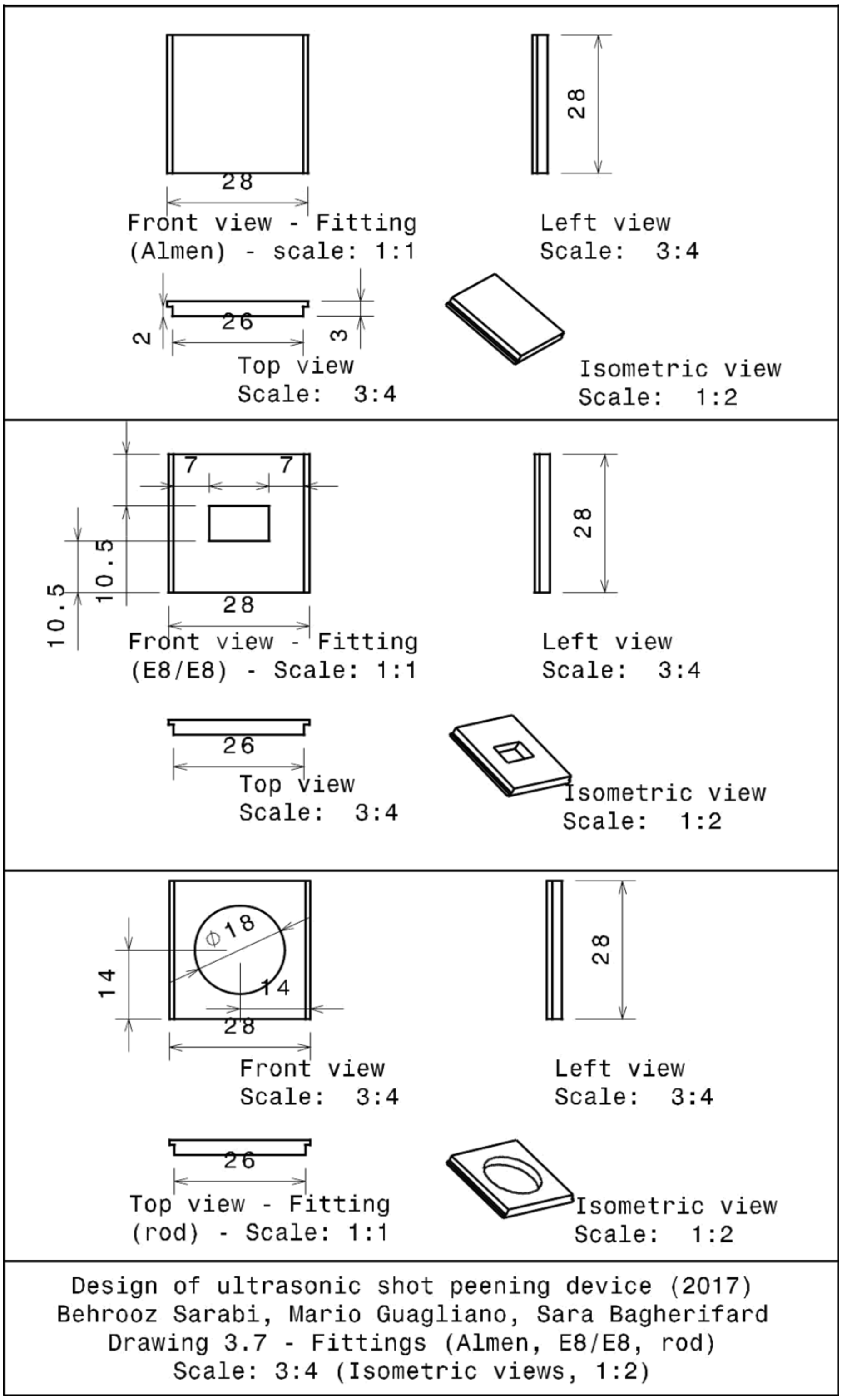


Figure 0.11 – Chamber ready for rod-shaped sample treatment



Drawing 0.7 – Fittings (Almen, E8/E8, Rod)

3.4 Choice of shots

3.4.1 Material of shots

The first step in choosing the material of the shots was a close study of the literature. Studies found that shots with 100C6 steel material need no replacement because of having a very high hardness. Therefore, they are mainly used for USP. [54] Some other materials that were used in labs and in the industry include stainless steel, hardened steel, 304-L, WC, ASIS 2100 bearing steel, SUJ2, zirconium oxide, tungsten carbide and high density ceramic shots. We chose to use the 100C6 steel as the material for our shots.

In Table 3.3, which is a summarization of our research on shots material, the influencing parameters, other materials used, and justification of our choice are presented.

Chosen Material	Remarks	Other materials used		Justification of material based on remarks/statistics
		material	diameter [mm]	
100C6 steel	Shots with 100C6 steel material need no replacement because of having a very high hardness. Therefore, they are mainly used for USP. [54]	stainless steel [37]	8 [37]	• This is the material most commonly used in the industry and literature. • Shots with this material need no replacement because of having a very high hardness. Therefore, they are mainly used for USP. [54]
		hardened steel [59]	8 [59]	
		304-L [68]	1-2 [68]	
		WC [69]	2-10 [69]	
		AISIS2100 bearing steel [70]	4 [70]	
		SUJ2 [71]	0.4 [71]	
		zirconium oxyde (Zy Premium from SiliBeads) [63]	2 [63]	
		stainless steel [72]		
		tungsten carbide [72]		
		high density ceramic [72]		

Table 0.3 – Shots: material selection

3.4.2 Dimension and number of shots

By a close study of the literature and relevant industrial products, the available range for the shot diameter was found to be between 0.4 and 8 mm.

We chose our shots' diameter to be 3 mm, and the number of thots to be around 181, since:

- This diameter was most commonly used in the literature for workpiece samples similar to ours.
- J. Badreddine et al. did a comparison of impacts on sonotrode, chamber, sample and shots, considering different parameters including the shot size, the amplitude of the sonotrode and the number of shots. [64] Based on their results, choosing 25 µm amplitude, 20 gram shots, 181 shots and 3 mm shots, seemed to be a good combination.
- This diameter suits well with the specifically small chamber size chosen.

In Table 3.4, the influencing parameters, available range of diameter, and justification of our choice regarding shot size and numbers are presented.

Chosen diameter [mm]	Chosen number	Remarks	Available range of diameter [mm]	Justification of radius and number of shots based on remarks/statistics
3	181 [64]	Comparison of impacts on sonotrode, chamber, sample and shots based on shot size, amplitude of sonotrode and number of shots shows that choosing 25 µm amplitude, 20 gram shots, and 181 shots and 3 mm shots (for a box slightly smaller in volume than our design) gives a good combination of desired effects: having high impact intensity on the workpiece while having low impact intensity on the sonotrode and chamber (longer life of chamber and sonotrode). [64]	0.4 - 8	• This diameter is most commonly used in the literature for workpiece samples similar to ours.. • J. Badreddine et.al [64] did a comparison of impacts on sonotrode, chamber, sample and shots, considering different parameters including shot size, amplitude of the sonotrode and number of shots. Based on his results, choosing 25 µm amplitude, 20 gram shots, 181 shots and 3 mm shots seemed to be a good combination of parameters. • This diameter suits well with the specifically small sized chamber chosen.

Table 0.4 – Shots: diameter and number selection

A general comment to be considered here is that this size of shots is suggested for the simple geometry of samples introduced here. For samples with more complex geometries, including notches and geometrical discontinuities, proper shot size should be selected according to the radius of the notch root et.

3.5 Choice of sonotrode

3.5.1 Amplitude of the sonotrode

The first step in choosing the sonotrode amplitude was to study closely the data in the literature and the commercially available products. In the literature, the amplitude was in the range 10-90 µm. However, in the industry much higher amplitudes were also used (250 µm). We chose the 25 µm amplitude for our sonotrode, since:

- This is the amplitude most commonly used in the literature for USP chambers with the dimensions (of chamber, shots and samples) close to ours.
- J. Badreddine et al. did a comparison of impacts on sonotrode, chamber, sample and shots, considering different parameters including shot size, amplitude of the sonotrode and number of shots. [64] Based on their results, choosing 25 µm amplitude, 20 gram shots, 181 shots and 3 mm shots seemed to be a good combination of parameters.
- A study shows that higher amplitude leads to higher surface roughness. [68] Also since our samples are of small dimensions, a high amplitude is not desirable.

Chosen amplitude	Remarks	Available range		Justification of chosen amplitude based on remarks/statistics
25 [µm]	Higher amplitudes give higher normal impact velocity. [64]	In the literature	10-90 [µm]	• Is the amplitude most commonly used in the literature for chambers with the dimensions close to ours.
	Maximum speed and normal component of velocity the velocity of the shots mainly depend on amplitude. [64]			

	Comparison of impacts on sonotrode, chamber, sample and shots based on shot size, amplitude of sonotrode and number of shots shows that choosing 25 μm amplitude, 20 gram shots, and 181 shots and 3 mm shots (for a box slightly smaller in volume than our design) gives a good balance of the desired properties: having high impact intensity on the workpiece and low impact intensity on the sonotrode and chamber (longer life). [64]			• J. Badreddine et.al [64] did a comparison of impacts on sonotrode, chamber, sample and shots, considering different parameters including shot size, amplitude of the sonotrode and number of shots. Based on his results, choosing 25 μm amplitude, 20 gram shots, 181 shots and 3 mm shots seemed to be a good combination of parameters. • The higher the amplitude, the higher would be surface roughness.
	The higher the amplitude, the higher would be surface roughness. [68]	In the industry [58]	10-250 [μm]	

Table 0.5 – Sonotrode: amplitude selection

3.5.2 Frequency and material of the sonotrode

A close study of the literature showed that as for the material for the end-part of the sonotrode (the surface contacting the shots), Titanium (Ti6Al4V) was unanimously used.

This led us to choose Titanium (Ti6Al4V) as the material of our sonotrode.

In the literature, the available range of frequency of sonotrode was found to be between 20 and 50 kHz. However, in the industry, lower frequencies (15 kHz) were also used.

We chose 20 kHz as the frequency for our sonotrode. This is because this frequency was almost unanimously used in the literature for designs similar to ours regarding their dimensions.

In Table 3.6, which is a summarization of our research on sonotrode frequency and material, the influencing parameters, the available range both in the literature and in the industry, and justification of our choices are presented.

Sonotrodes with different sizes and technical specifications are available in the market, among which 20 kHz frequency and titanium-made sonotrodes seem broadly available. Also, many of the sonotrode producers customize their product based on the requirements of the customer. Thus, procuring a sonotrode with our chosen specifications can be easily achieved. We asked SonicItalia the price of a custom-made sonotrode with square cross section end part (74*74 mm), titanium

(Ti6Al4V) made, 20 kHz frequency and 25 µm amplitude, and they offered us a purchase price of 3001,20 Euros. As an option for procurement of the sonotrode, also Emerson, and Hielscher companies can be named.

Chosen frequency	Chosen material	Available range		Justification of chosen frequency based on remarks/statistics	Justification of chosen material based on remarks/statistics
20 [kHz]	Titanium (Ti6Al4V)	In the literature	20 or 50 [kHz]	• It Is the frequency most often used in Literature (there was only a single use of 50 kHz frequency). • Is among the common frequency range used in the industry.	This material was used unanimously in all articles.
		In the industry [58]	15 or 20 or 40 [kHz]		

Table 0.6 – Sonotrode: frequency and material selection

3.6. Solution for rotating the E466-15 rod-shaped sample

As discussed in section 3.2.3, our E466-15 rod-shaped sample needs to be rotated at a low and constant speed. The rotating motion of the rod can be achieved by using an electric motor. Since a portion of the rod is left outside the chamber, the electric motor does not need to be placed inside the chamber. Since the rod sample in not heavy and its weigh is supported by the bearings, our electric motor does not need to have high torque. Thus, many options are available: any AC or DC motor with low torque and low speeds (ranging from few rounds per minute to 60 rpm) can be of use. The prices of such motors can range from 15 to 150 euros. As an option, we suggest a motor with the following specifications which can be procured for around 30 euros in the market:

- 12V DC
- 60RPM

- Diameter: 37mm
- Length (excluding shaft): 47mm
- Shaft length: 21mm
- Total length: 68mm
- Shaft diameter: 6mm
- Weight: 138g

3.7 Vacuuming solution

As discussed before, we need our USP treatment to be performed in vacuum conditions to avoid possible oxidation of the exposed surface. Because of the rotating motion of our rod-shaped sample, it is difficult to vacuum-seal our chamber. As a solution to this, and since the overall size of our system (including the chamber, the sonotrode, and the electric motor) is not very big, we decided to put the whole system in a box-shaped vacuum chamber. Below are presented the calculations of the overall dimensions of our system (equal to the minimum required inner volume of the vacuum chamber):

- Our chamber would have its maximum length when it carries the rod-shaped chamber, which is 120 mm. Since also the electric motor needs to be attached to the rod (max length 68 mm), our overall length at maximum would be 20.0 cm (considering also the connectors between the motor and the sample).
- Our chamber has a width of 10.6 cm, which is our overall maximum width. Thus, we can say the maximum of the system to be vacuumed would be 11 cm (rounded up).
- The overall height of our chamber (including the lid height) would be 64 mm (45+19 mm). Also, considering 70 mm for the height of the ending part of the sonotrode (called the horn), of which 5 mm is placed inside the chamber, our overall height would reach a maximum of 14 cm (rounded up).

Considering the above calculations, we would need a chamber whose minimum inner dimensions are: 20*11*14 cm. (length*width*height)

Pre-made industrial vacuum chambers in different sizes, materials, and prices, are available to purchase from different sources in the market. These companies often customize their chambers based on the specific requirements of the customer.

As an example, TerraUniversal produces a premade vacuum chamber (Acrylic vacuum chamber, model B) with inner dimensions 28*28*14 cm (length*height*width) and for a price of 1321 US dollars, which can be a suitable option for our purpose. As other options for procurement of the vacuum chamber, Pfeiffer Vacuum, Laco Technologies, ASLI and Highlight Tech Corp. companies can be named.

3.8 Three-dimensional rendering of our ultrasonic shot peening device

In the pictures 3.12 to 3.18, will be presented the 3D rendering of our designed USP device ready to shot peen each of our three samples.

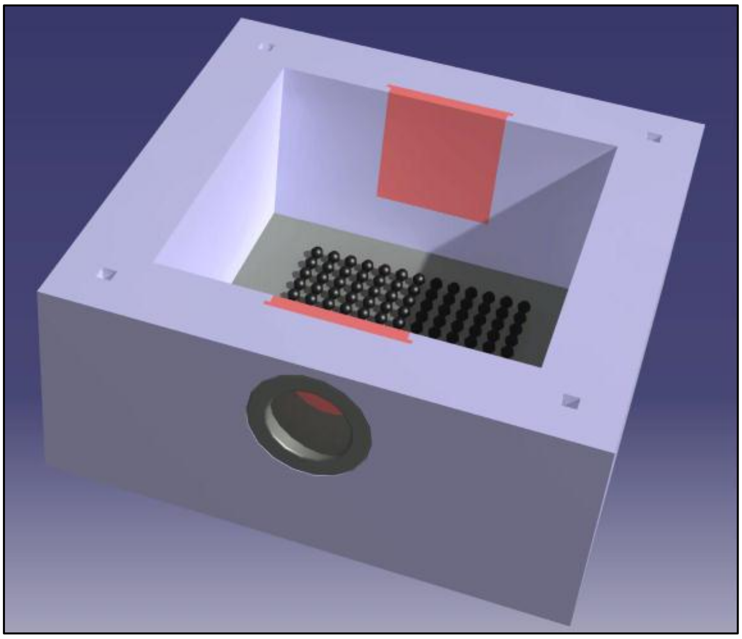


Figure 0.12 – 3D render of our USP device; Almen strip treatment mode (view 1)

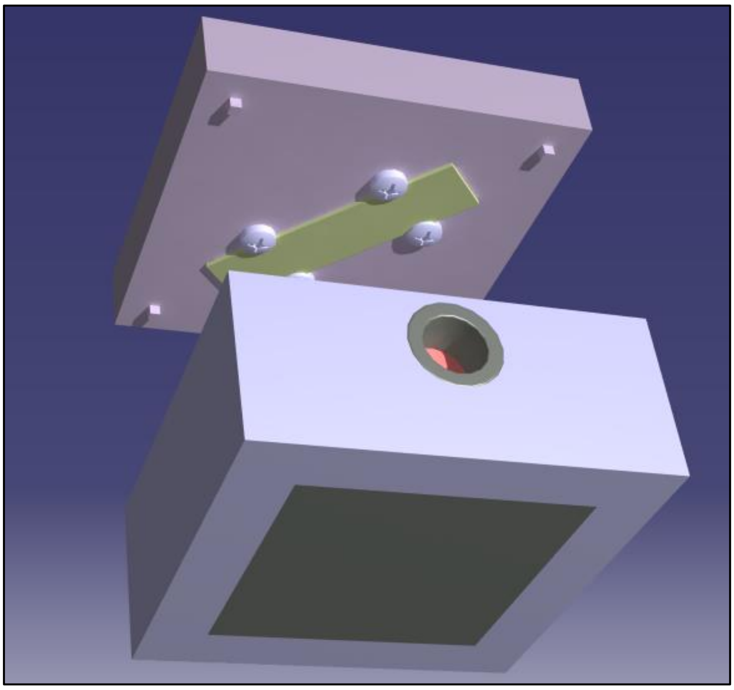


Figure 3.13 – 3D render of our USP device; Almen strip treatment mode (view 2)

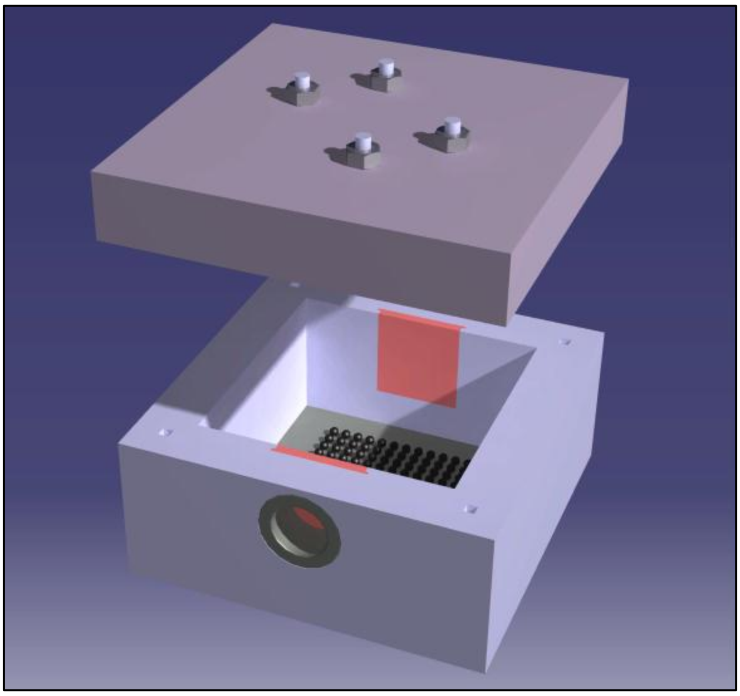


Figure 0.14 – 3D render of our USP device; Almen strip treatment mode (view 3)

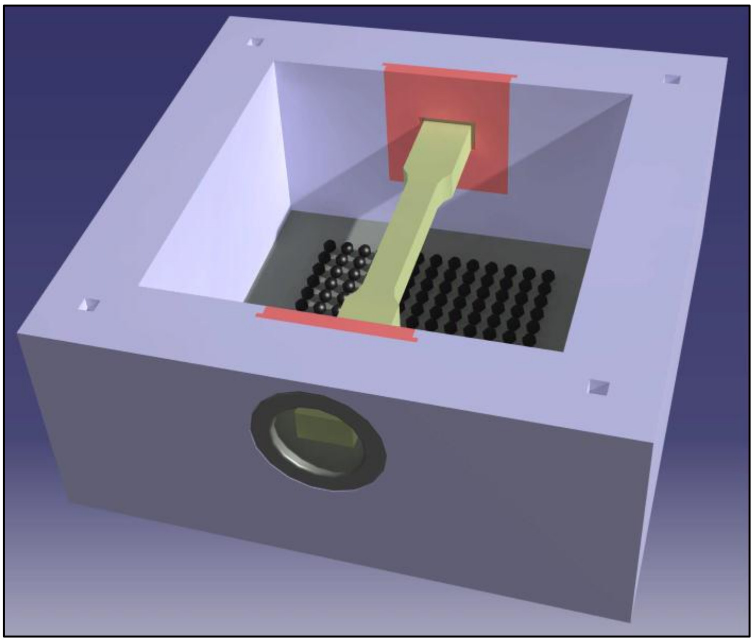


Figure 0.15 – 3D render of our USP device; E8/E8 sample plate treatment mode (view 1)

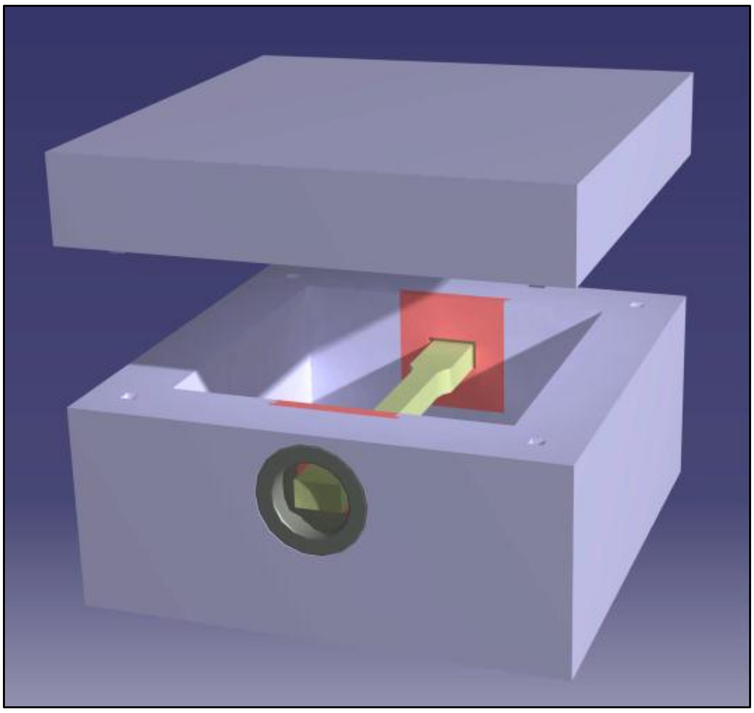


Figure 0.16 – 3D render of our USP device; E8/E8 sample treatment mode (view 2)

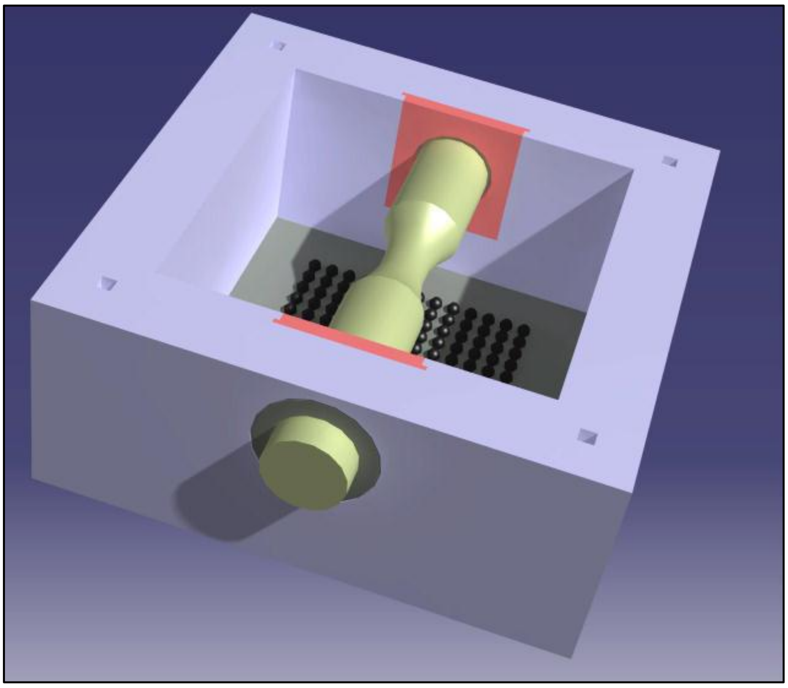


Figure 0.17 – 3D render of our USP device; E466-15 sample treatment mode (view 1)

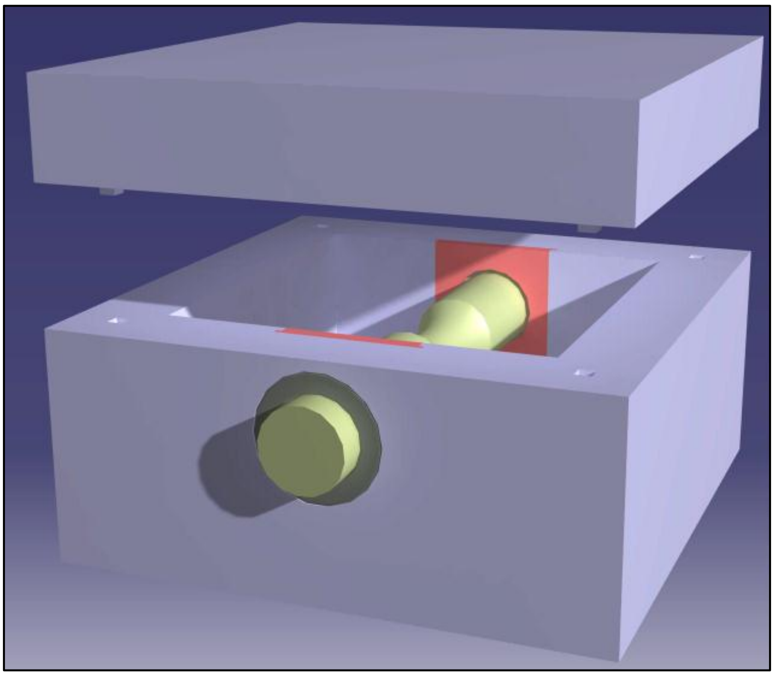


Figure 0.18 – 3D render of our USP device; E466-15 sample treatment mode (view 2)

4. Possible future developments: Design of warm ultrasonic shot peening device for magnesium alloy sample

Magnesium alloys were one of the sample workpiece material groups that we were interested to shot peen with our device.

Due to their high stiffness and specific strength and their lower weight for having a low density, magnesium alloys seem to be an interesting alternative for aluminum alloys in automotive industry. [73] [74] However, when compared to Al alloys, their lower fatigue strengths and higher environmental sensitivity restrict their applicability. [75]

As discussed in previous chapters, shot peening is one of the surface treatment methods that can significantly enhance the fatigue life of metallic materials. However, the available data acquired by experiments shows that shot peened wrought magnesium alloys show an over peening effect with low optimum Almen intensity. The reason for this can be the limited deformability of the hexagonal crystal structure for magnesium alloy at room temperature. [76]

Studies show that for magnesium alloy with the hexagonal crystal structure, non-basal slip system would be activated at temperatures higher than 225º C and ductility is greatly enhanced. [77] Therefore, warm (air blast) shot peening has been proposed by scientists as a method of improving the fatigue properties of magnesium alloys. This was confirmed by the empirical results showing that warm air blast shot peening improves the fatigue life of the magnesium alloy compared to the conventional shot peening method. [78]

As a possibility for future development of our designed device, we decided to propose a brand-new method for peening the magnesium alloy samples at high temperatures: warm ultrasonic shot peening (WUSP).

Being a brand-new method, no empirical data existed in the literature regarding this treatment. Thus, our design for the WUSP device was limited to proposing a shape-design and material for the device in such a way that fulfills both our vacuuming and high temperature requirements at the same time. Further investigation on our WUSP design needs to be done and the validity of our propositions for WUSP need to be either experimentally or by help of simulation methods confirmed.

In the following sections of this chapter, the shape design of the device would be presented and explained, and the choices of materials for the chamber will be explained.

4.1 Sample to be warm ultrasonic shot peened

As discussed above, our sample workpiece's material to be treated with our WUSP device, would be an alloy of magnesium which needs to be shot peened at temperatures higher than 225º C.

Regarding the shape, our designed WUSP device is limited to treating plate-shaped sample workpieces, with geometries identical to the ASTM E8/E8M – 09 plate tensile test sample.

The geometries of this sample workpiece are presented in section 3.2.2.

4.2 Chamber shape-design for the warm ultrasonic shot peening device

As explained before, for our WUSP device we need to reach temperatures above 225º C, and we also need to have vacuum conditions.

However, unlike our previous design case (ultrasonic shot peening at room temperatures), using a separate vacuum chamber to encompass our peening system is not a suitable solution here: If the peening chamber itself is not vacuum (and heat) sealed, the heat will be transferred to the vacuum chamber. Thus, we would require our vacuum chamber to be specifically designed to withstand high temperatures, which costs a lot. Moreover, by doing so, we would need all the machine parts inside our vacuum chamber (like the sonotrode horn, electrical cables, etc.), to be resistant to high temperatures, which will also add up to the costs.

As a solution to this problem, we proposed a completely different design shape for our WUSP peening-chamber, making it at the same time vacuum and heat sealed on its own. By doing so, the need for a separate vacuum chamber was eliminated.

This, off course, made the shape design of our WUSP peening chamber much more complex, and made it necessary to use some additional components. The working mechanism of our device would be explained in the next section, accompanied by drawings and figures.

4.2.3 Explanation of the working mechanism of our warm ultrasonic shot peening chamber

As discussed before, our WUSP peening chamber is designed in a way that it peens the workpiece at high temperatures while it is also vacuum sealed. Our peening chamber, illustrated in Figure 4.1, is composed of these parts:

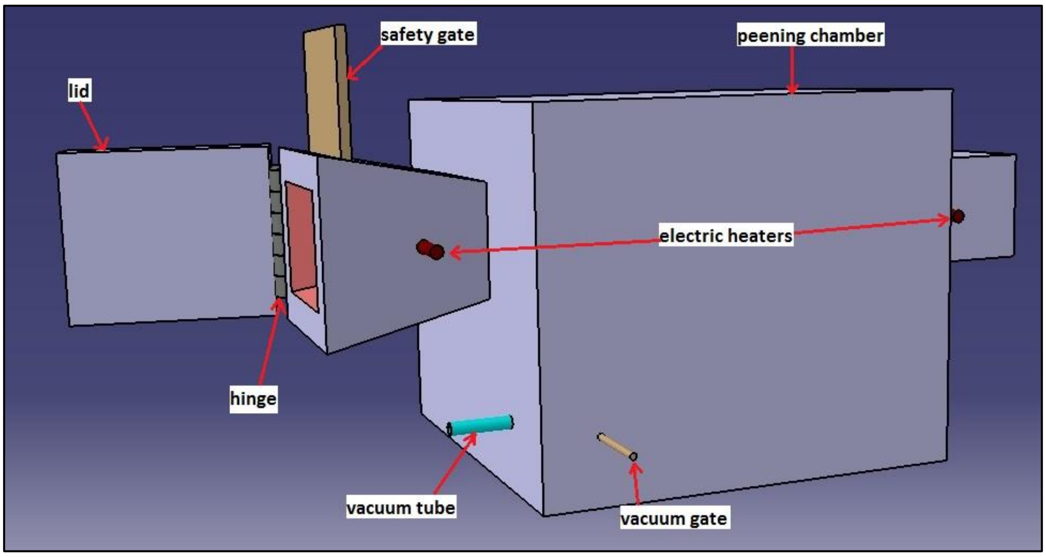


Figure 0.1 – WUSP peening chamber

- The main body of the peening chamber.
- The lid, which completely closes the only gap connecting the inside space of the chamber to the surroundings.
- The hinges, connecting the lid to the main body.
- The secondary (safety) gate, which protects the lid from direct heat of the heaters.

- The two electric heaters, which have a direct contact with the surface of the workpiece at its two ends, and have the role to increasing its temperature to the desired one.
- The vacuum tube, which is connected from outside to a compressor and is the medium through which the air inside the chamber is vacuumed.
- The vacuum gate, which working as an isolator, blocks the heat from entering the vacuum tube and the compressor.

To better explain the working mechanism of our device, we used sectioned illustrations, showing the device respectively in each of its six working stages:

- Stage 1: Figure 4-2 shows the empty chamber, ready to insert the sample workpiece. In this figure one can see the main body of the chamber and the opened lid (light gray), two electric heaters (red), the secondary gate (light brown), and the sonotrode (at the bottom of the chamber, dark gray)

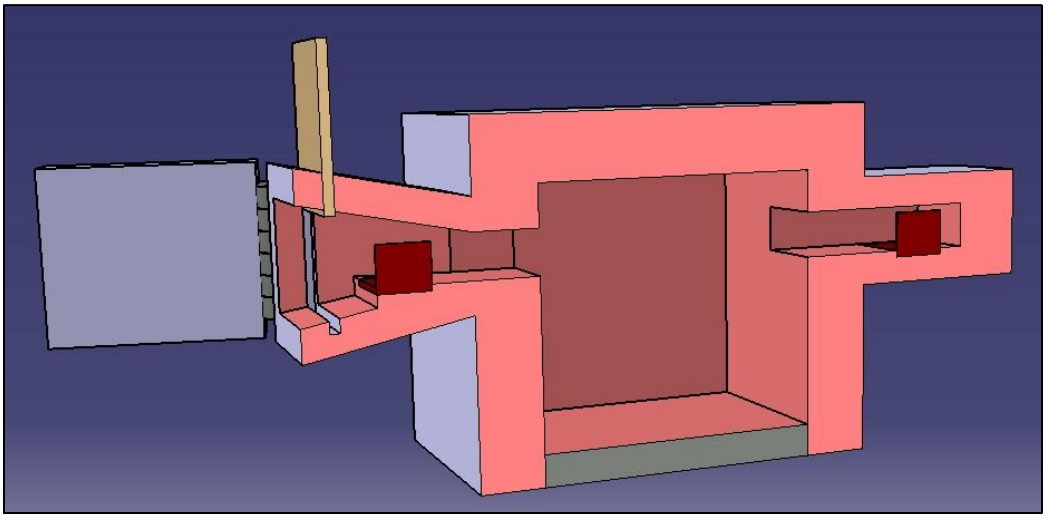


Figure 0.2 – Working stages of the WUSP chamber; Stage 1: Empty chamber, ready to put in the sample workpiece.

- Stage 2: Figure 4.3 shows the sample workpiece (green) inserted inside the chamber.

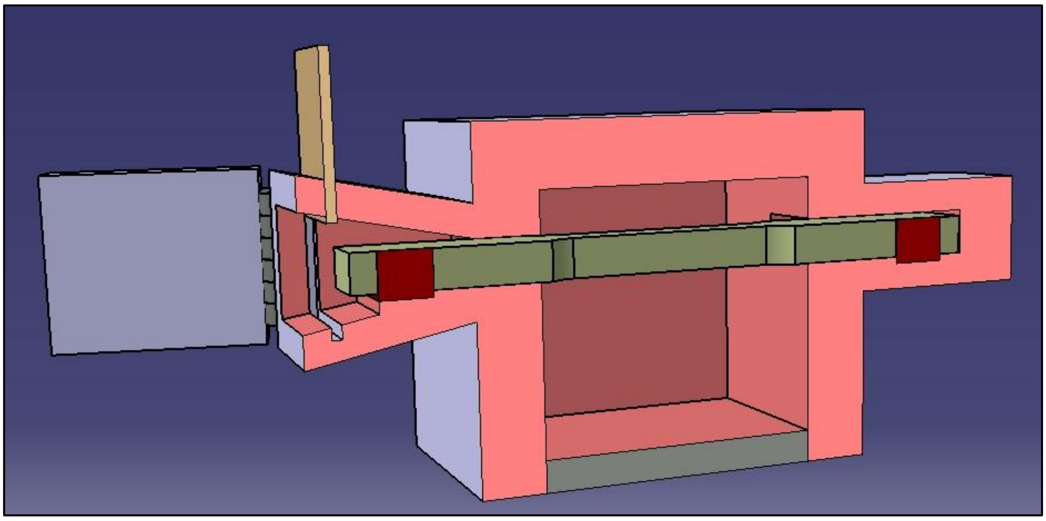


Figure 0.3 – Working stages of the WUSP chamber; Stage 2: Sample workpiece (green) inserted inside the chamber.

- Stage 3: The safety gate and the lid are closed.

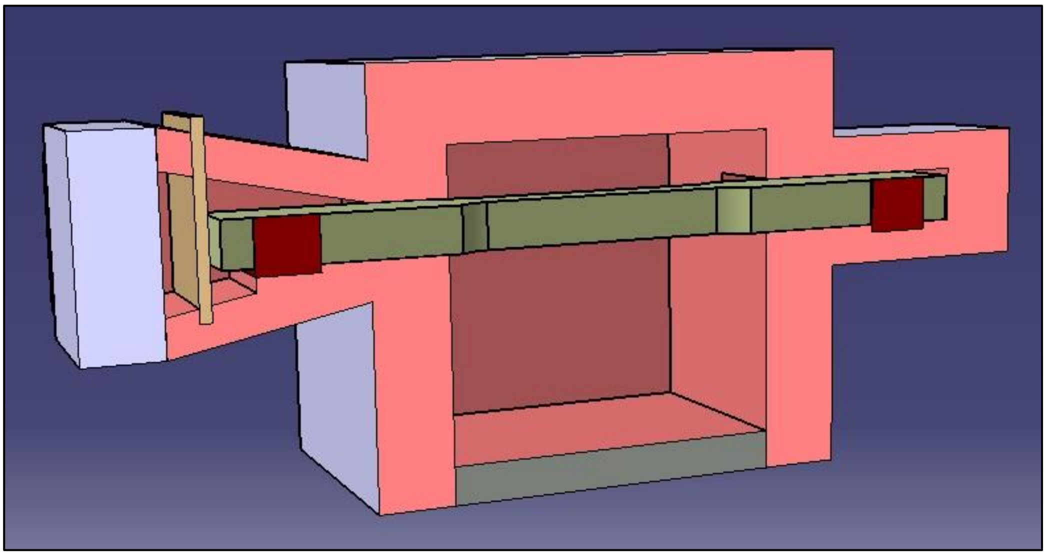


Figure 4.4 – Working stages of the WUSP chamber; Stage 3: The safety gate and the lid are closed.

- Stage 4: The chamber is vacuumed via the vacuum tube (blue).

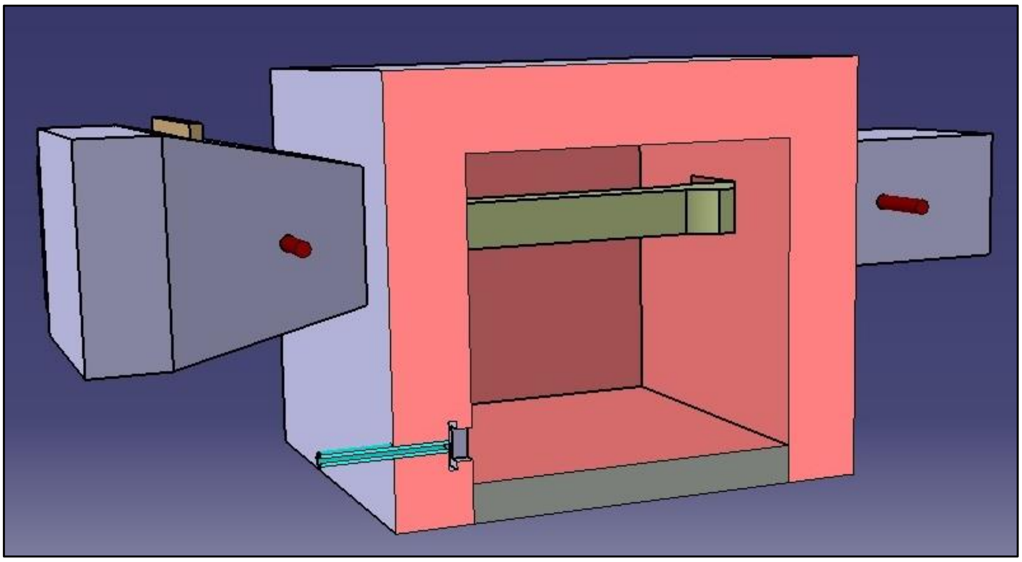


Figure 0.5 – Working stages of the WUSP chamber; Stage 4: The chamber is vacuumed via the vacuum tube.

- Stage 5: After vacuuming, the vacuum gate (cream) is closed to protect the vacuuming system (tube and the compressor) from the heat.

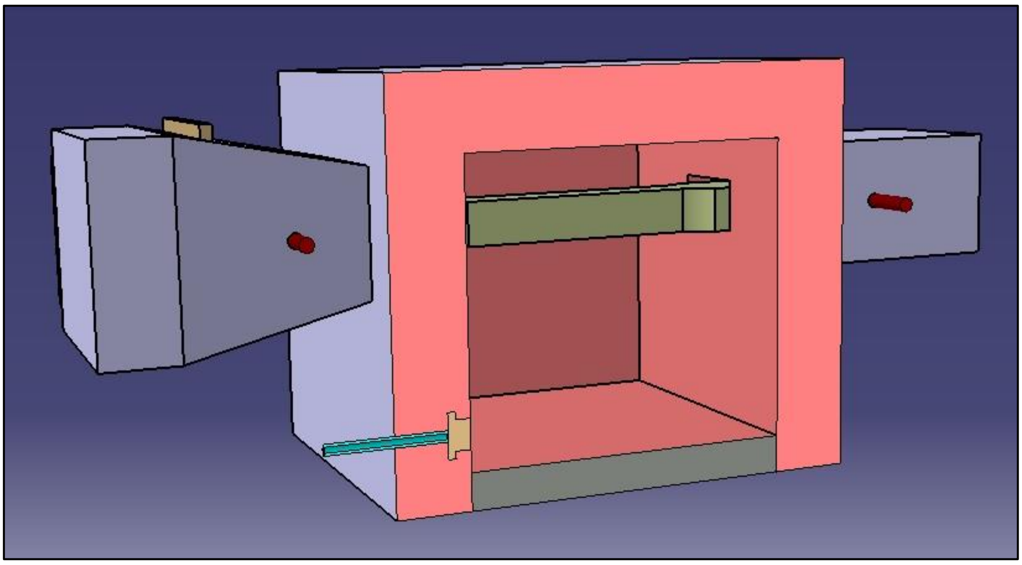


Figure 0.6 – Working stages of the WUSP chamber; Stage 5: Vacuum gate is closed.

- Stage 6: The electric heaters are turned on and the sample workpiece reaches the desired temperature, ready to be shot peened.

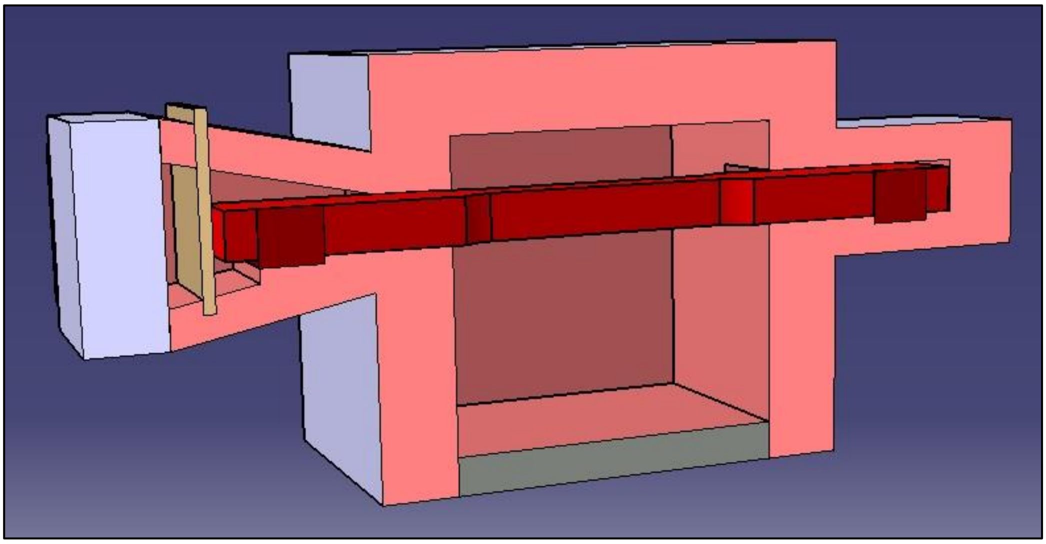
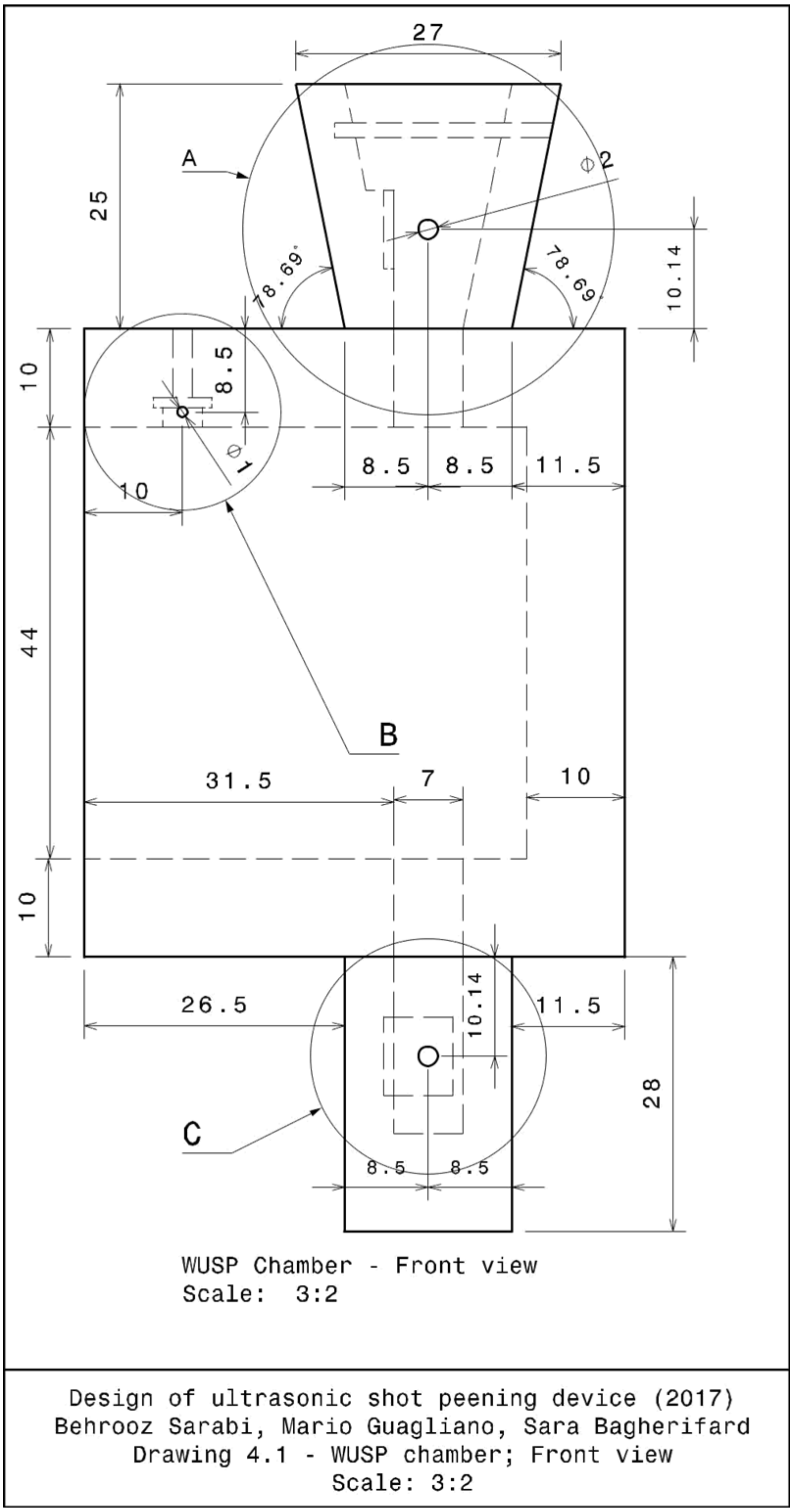
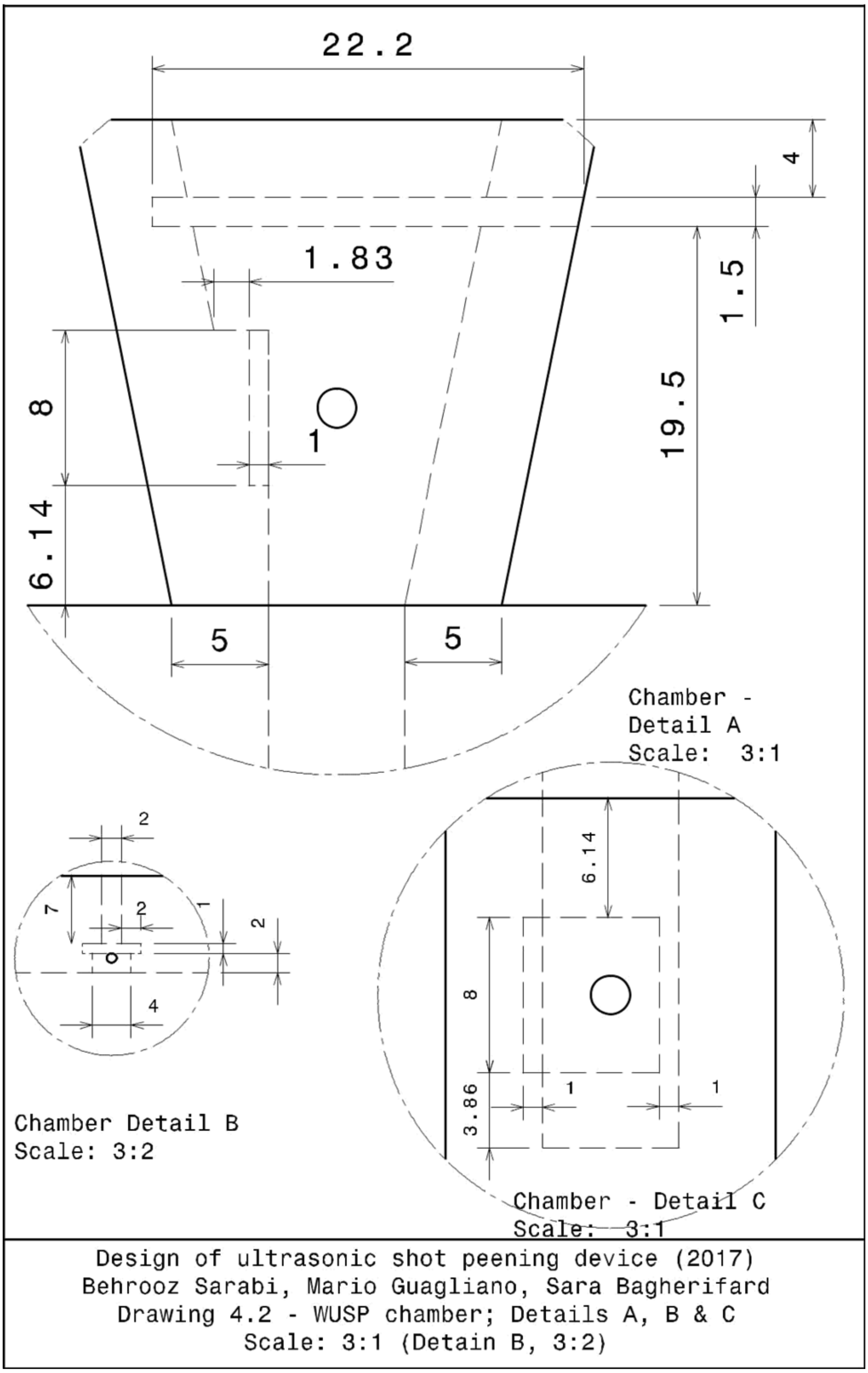


Figure 0.7 – Working stages of the WUSP chamber; Stage 6: The electric heaters are turned on and the sample workpiece reaches the desired temperature, ready to be shot peened.

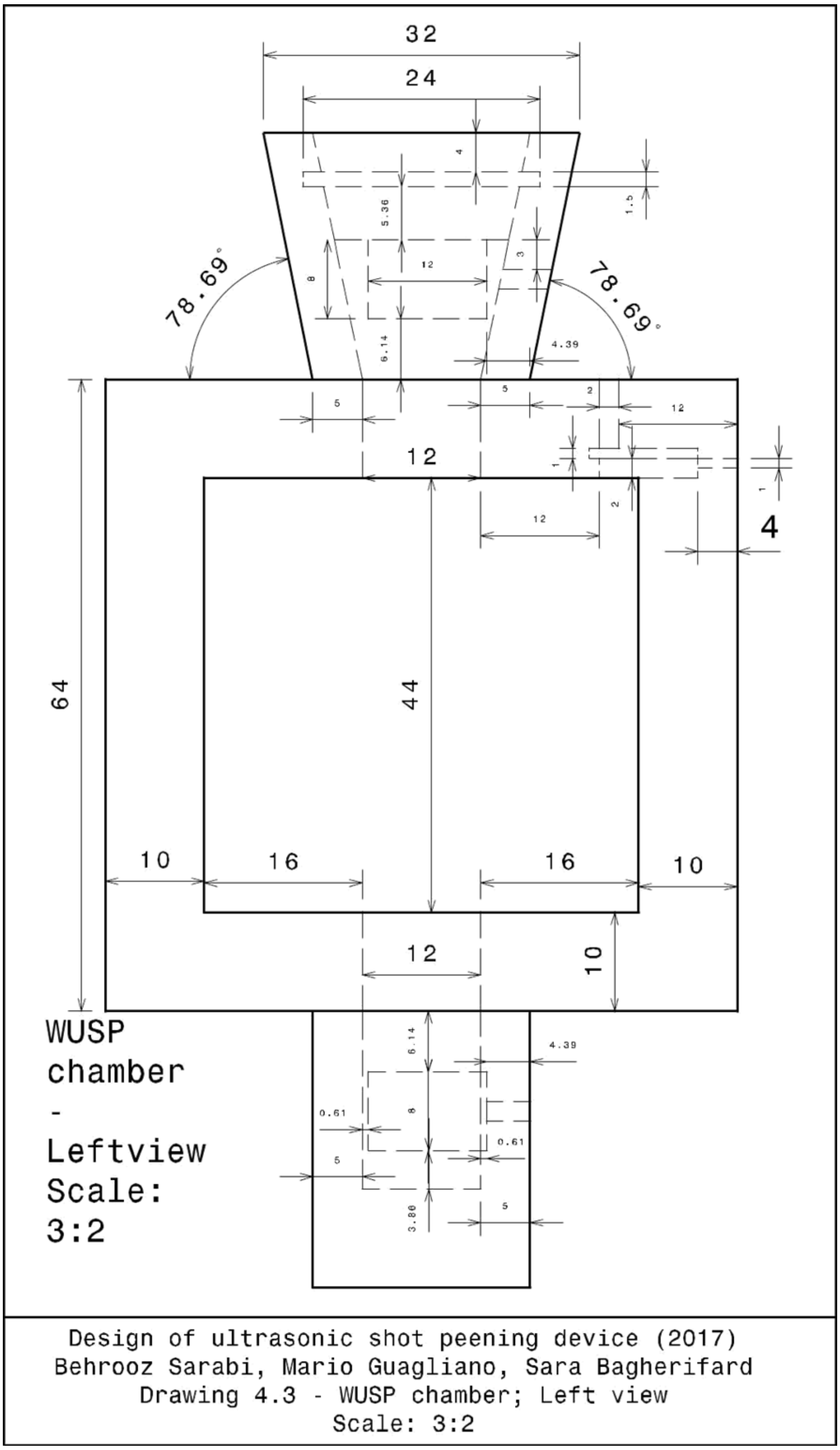
The dimensions of our WUSP designed chamber and its additional components are presented in Drawings 4.1 to 4.7.



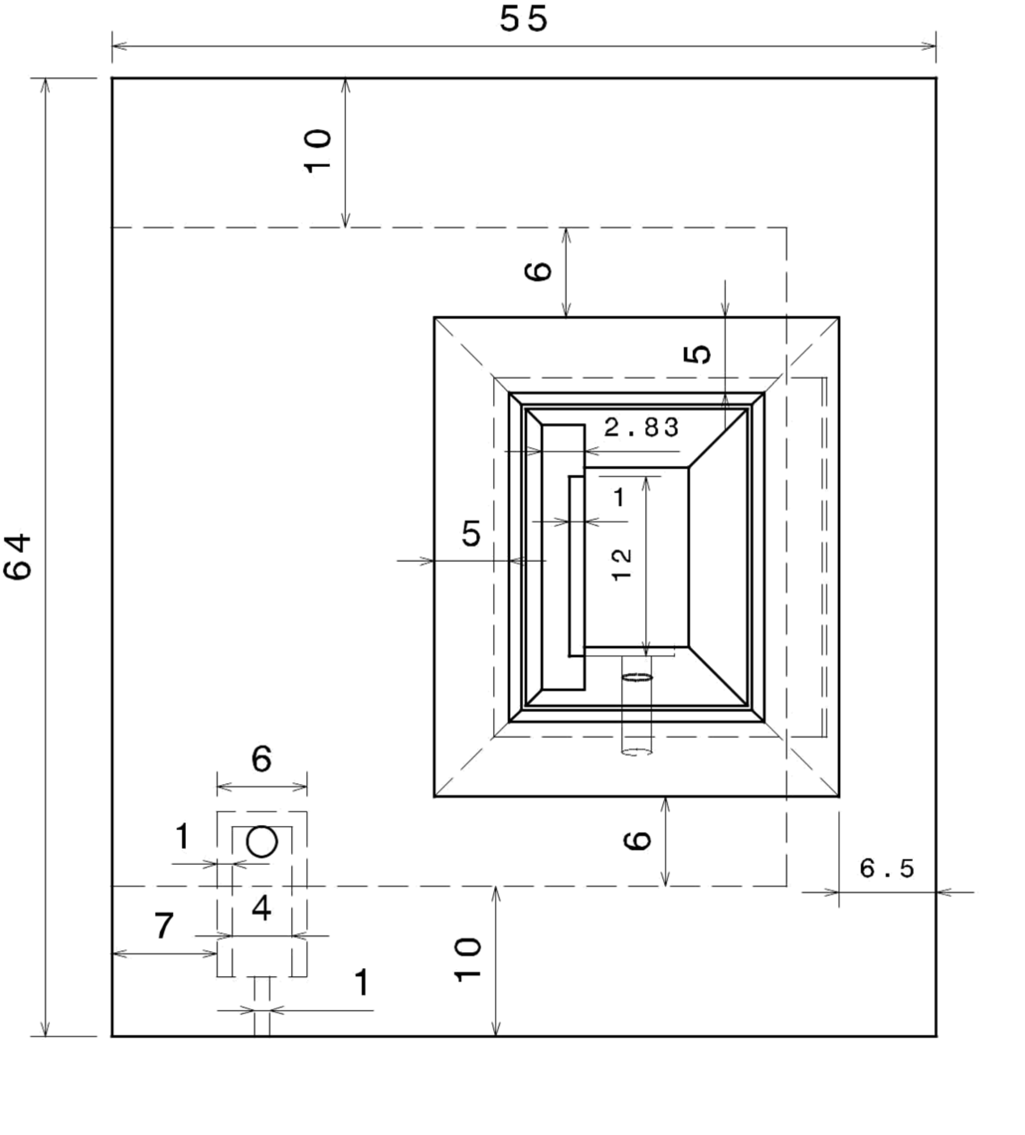
Drawing 0.1 – WUSP chamber; Front view



Drawing 0.2 – WUSP chamber; Details A, B & C

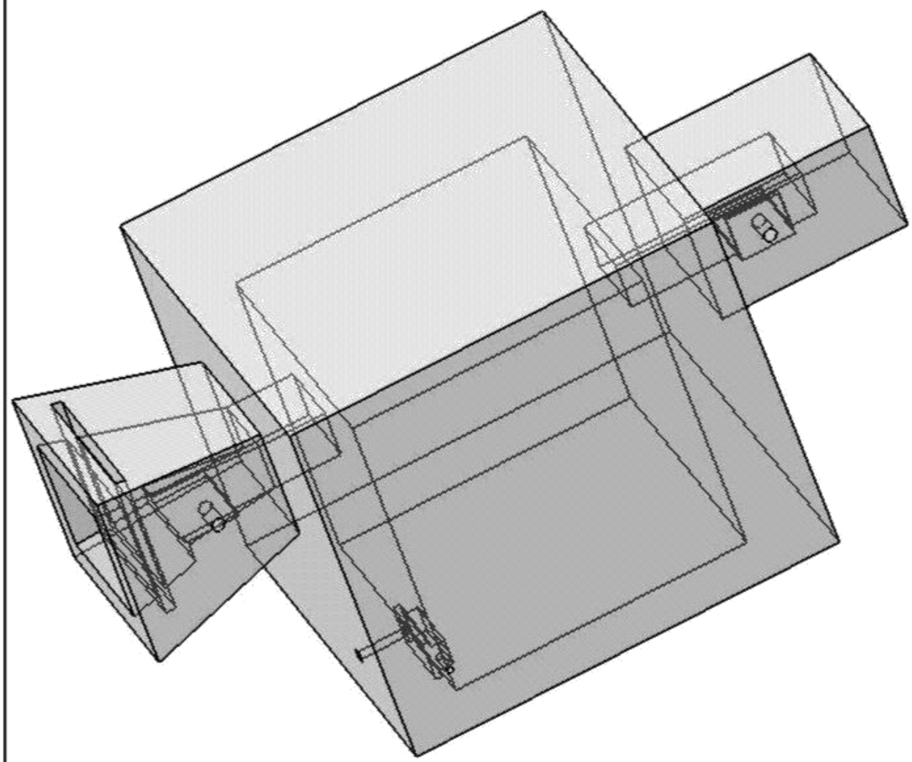


Drawing 0.3 – WUSP chamber; Left view



Design of ultrasonic shot peening device (2017)
Behrooz Sarabi, Mario Guagliano, Sara Bagherifard
Drawing 4.4 - WUSP chamber; Top view
Scale: 2:1

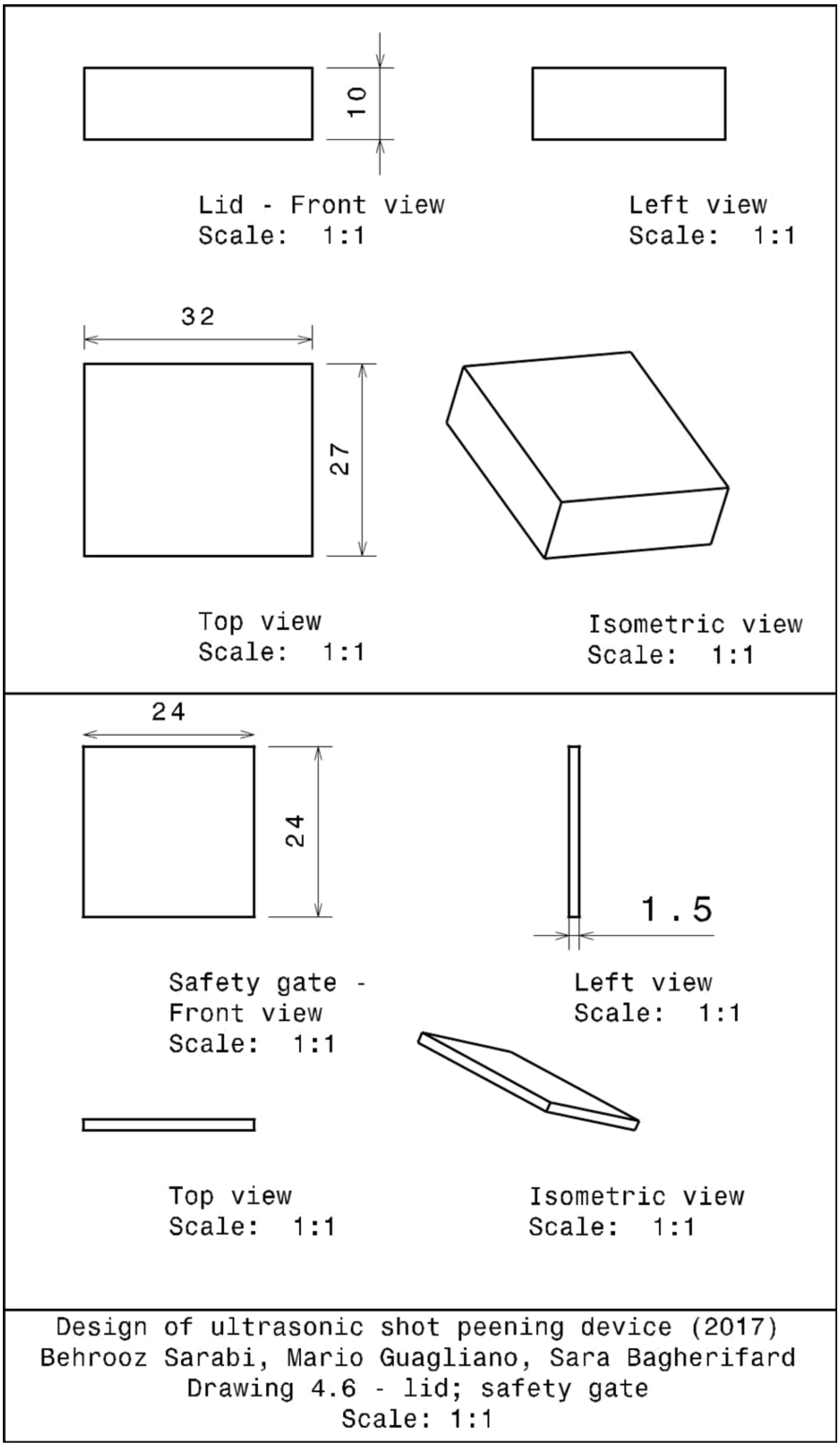
Drawing 0.4 – WUSP chamber; Top view



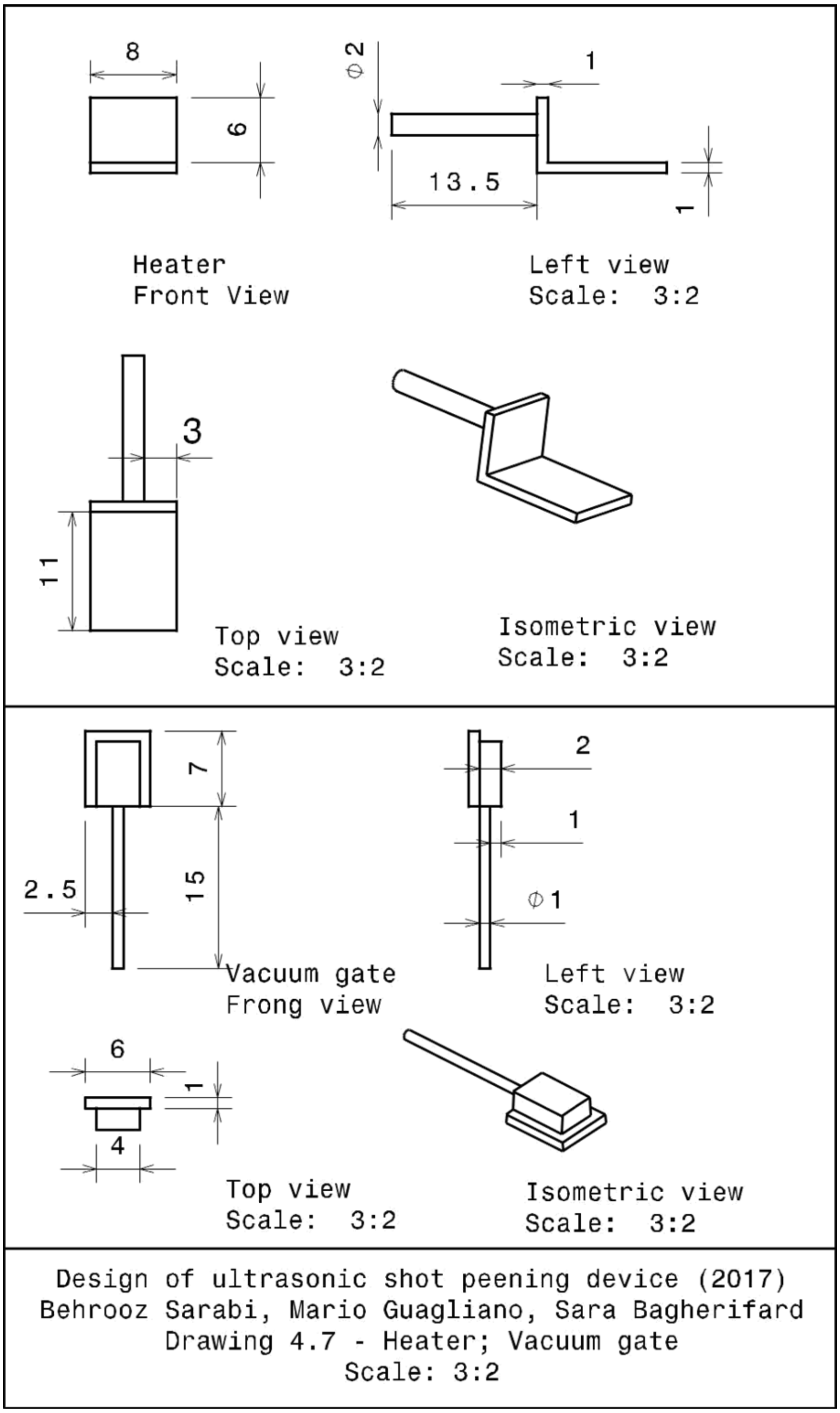
WUSP chamber -
Isometric view - Scale:
1:1

Design of ultrasonic shot peening device (2017)
Behrooz Sarabi, Mario Guagliano, Sara Bagherifard
Drawing 4.5 - WUSP chamber; Isometric view
Scale: 1:1

Drawing 0.5 – WUSP chamber; Isometric view



Drawing 4.6 – Lid; Safety gate (for WUSP chamber)



Drawing 0.7 – Heater; Vacuum gate (for WUSP chamber)

4.3 Chamber material selection for the warm ultrasonic shot peening device

As discussed in chapter three, we chose hardened steel as the material of the body of our ultrasonic shot peening chamber which was working at room temperature conditions. However, for WUSP device, hardened steel does not seem to be a good choice:

On one hand, the high thermal conductivity of the hardened steel causes both heat (energy) loss, and damage to the surroundings and other device components (wires, electric parts etc.). On the other hand, peening at high temperatures can strongly accelerate the various types of mechanical failure of the chamber (fatigue failure, deformation, corrosion, etc.).

To solve the problem of insulation, we propose using ceramic composites (widely used in high temperature furnaces) as the material for the main body of the chamber. To protect the ceramic from the high pressure of the shot impacts, we propose either making a protective layer (or coating) of Inconel alloys, for the inner surfaces of the peening chamber.

Inconel alloys are oxidation- and corrosion-resistant materials commonly used in extreme working environments subjected to pressure and heat. Inconel maintains strength over a wide temperature range, making it an interesting choice for high temperature applications where aluminum and steel would fail to creep as a result of thermally induced crystal vacancies. [79] [80]

5. Conclusion and suggestions

Despite its recent growth in industrial applications, ultrasonic shot peening technology lacks the machinery in the university of Politecnico di Milano, making further development of the technology and studying its effects on different materials challenging. We therefore decided to propose a design model for production of an ultrasonic shot peening device, accompanied with detailed technical specification for each of the device components.

To do so, a close study of the literature and relative industrial products was done, and the acceptable range for each design parameter was found out. Then, based on the geometry of our workpiece models of interest for shot peening (the Almen strip, the ASTM E8/E8M – 09 plate tensile test sample, and the ASTM E466-15 rod-shaped tensile test sample), the best design parameters were chosen among the acceptable range, each provided with justifications. Below, our design choices for different device components are summarized:

- Chamber shape: box-shaped
- Chamber inner dimensions: 40*74*74 mm (height*width*length)
- Chamber wall thickness: 16 mm (19 mm for the lid)
- Chamber material: hardened steel
- Bearings: 13*16*24 mm (width*inner diameter*outer diameter)
- Shots material: 100C6 steel
- Shots diameter: 3 mm
- Number of shots: 181
- Sonotrode amplitude: 25 µm
- Sonotrode frequency: 20 kHz
- Sonotrode material: Titanium (Ti6Al4V)
- Vacuum chamber minimum inner dimensions: 28*28*14 cm (lenght*width*height)

Then, a specific shape-design for the peening chamber (which in ultrasonic shot peening is commonly specialized based on the sample workpiece) was presented, accompanied with engineering drawings and 3-D CAD models and renderings.

As a possibility for future development of our design, we considered a complete different type of sample workpiece (magnesium alloys), which needs to be shot peened at high temperatures. Therefore, based on our studies on ultrasonic shot peening, we proposed a brand-new technology, called warm ultrasonic shot peening (WUSP), which is ultrasonic shot peening of the magnesium sample at temperatures higher than 225º C. To fulfill the vacuum and high temperature requirements simultaneously, we then designed a specific chamber (accompanied by engineering drawings and 3-D CAD models and renderings) for our WUSP device, and proposed ceramic composites as the chamber material with a coating of Inconel alloy for its inner surface.

For further development and improvement of our WUSP device, empirical or simulation based results need to be obtained and validity of our choices need to be verified. Moreover, accessories for controlling the temperature need to be devised inside the chamber. Also, design of a WUSP chamber with the ability to rotate the workpiece sample can be considered as an interesting development of the device.

References

[1] "Shot Peening," in *Tool and Manufacturing Engineers Handbook (TMEH), Volume 3*, Society of Manufacturing Engineers, 1985.

[2] "www.ceramics.org," [Online]. Available: http://ceramics.org/ceramic-tech-today/manufacturing/removing-distortion-from-thin-ceramics-with-shot-peening.

[3] [Online]. Available: http://www.sae.org/standards/.

[4] Y. Todaka, M. Umemoto, J. Li and K. Tsuchiya, in *Rev. Adv.Master.s Sci.*, 2005, 10, pp. 409-416.

[5] Y. Todaka, M. Umemoto and K. Tsuchiya, in *Mater. Trans.*, 2004, 45, pp. 376-379.

[6] M. Umemoto, Y. Todaka and K. Tsuchiya, in *Mater. Trans.*, 2003, 44, (7), pp. 1488-1493.

[7] J. Y. a. B. D. ,. 2. 2. T. Wang, in *Sruf. Coat Technol.*, 2006, 200, pp. 4777-4781.

[8] M. Umemoto, Y. Todaka and J. Etastab, in *Nanocryst. Mater.*, 2005, pp. 24-25; 571-576.

[9] [Online]. Available: http://www.mecpl.com/standared-blasting-cabinets.php#.

[10] S. Bagheri and M. Guagliano, "Review of shot peening processes to obtain nanocrystalline surfaces in metal alloys," pp. 3-14, 2009.

[11] X. Y. Wang and D. Y. Li, in *Electrochim. Acta*, 2002, 47, p. 3939–3947.

[12] X. Y. W. J. X. L. D. Y. L. X. P. Jiang, C. S. Manc, M. J. Shepard and T. Zhai, in *Mater. Sci. Eng. A*, 2006, 429, p. 30–35.

[13] L. Wang and D. Y. Li, in *Surf. Coat. technol.*, 2003, 167, p. 188–196.

[14] L. Wang and D. Y. Li, in *Wear*, 2003, 255, p. 836–845.

[15] L. Wang and D. Y. Li, in *Surf. Coat. technol.*, 2003, 167, p. 188–196.

[16] J. X. Deng, Y. H. Feng, Z. L. Ding and P. W. Shi, in *J. Eur. Ceram.Soc.*, 2003, 23, p. 323–329.

[17] [Online]. Available: http://www.pshotblast.com/paver-blasting-machines.php.

[18] [Online]. Available: http://www.eaglemasterinc.com/services/shot-peening/.

[19] [Online]. Available: http://www.wheelabratorgroup.com/en/sites/wheelabrator/content/about_us/about_wheelabrator/what_is_shot_peening.aspx.

[20] A. J. O and B. P. H, "Residual stresses and fatigue in metals," 1963.

[21] B. S and M. P, "Shot peening: a dynamic application and its future," 2009.

[22] Kirk and David, "Non-Uniformity of Shot Peening Coverage," in *The Shot Peener*, Electronics, Inc., Summer 2009.

[23] R. K. Pandey and M. N. Deshmukh, "SHOT PEENING AND ITS IMPACT ON FATIGUE LIFE OF ENGINEERING COMPONENTS," in *International Conference on Shot Peening and Blast Cleaning*, Delhi.

[24] "DISA Makes an Impact on The Science and Technology of Shot-Peening," *Metal Finishing News,* no. March, 2006.

[25] Haverty, Donncha and B. Kennedy, "Shot Peening: A Powerful Surface Coating Tool for Biomedical Implants," *The Shot Peener, Electronics, Inc.,* no. Summer, 2009.

[26] R. W. Cahn, *Nature,* no. 348, pp. 389-390, 1990.

[27] T. Kulik, *J. Non-cryst. Solids,* no. 287, pp. 145-161, 2001.

[28] Y. Todaka, M. Umemoto, Y. Watanabe and K. Tsuchiya, *Mater. Sci. Forum,* pp. 503-504; 669-674, 2006.

[29] J. L. Liu, M. Umemoto, Y. Todaka and K. Tsuchiya, *J. Mater. Sci.,* vol. 42, pp. 7716-7720, 2007.

[30] T. Kulik, in *J. Non-cryst. Solids*, 2001, 287, p. 145–161.

[31] G. Liu, J. Lu and K. Lu, in *Mater. Sci. Eng. A*, 2000, 286, p. 91–95.

[32] K. Lu and J. Lu, "Surface Nanocrystallization (SNC) of Metallic Materials-Presentation of the Concept behind a New Approach," *J. Master. Sci. Technol,* vol. 15, p. 193–197, 1999.

[33] Y. Lin, J. Lu, L. Wang, T. Xu and Q. Xue, in *Acta Mater.*, 2006, 54, p. 5599–5605.

[34] H. W. Zhang, Z. K. Hei, G. Liu, J. Lu and K. Lu, in *Acta Mater.*, 2003, 51, p. 1871–1881.

[35] N. R. Tao, M. L. Sui, J. Lu and K. Lua, in *Nanostruct. Mater.*, 1999, 11, pp. 433-440.

[36] X. Wu, N. Tao, Y. Hong, B. Xu, J. Lu and K. Lu, in *Acta Mater.*, 2002, 50, pp. 2075-2084.

[37] N. R. Tao, Z. B. Wang, W. P. Tong, M. L. Sui, J. Lu and K. Lu, in *Acta Mater.*, 2002, 50, p. 4603–4616.

[38] Y. Lin, J. Lu, L. Wang, T. Xu and Q. Xue, in *Acta Mater.*, 2006, 54,, p. 5599–5605.

[39] G. Liu, S. C. Wang, X. F. Lou, J. Lu and K. Lu, in *Scr. Mater.*, 2001, 44, p. 1791–1795.

[40] Ochi, K. Masaki, T. Matsumura and T. Sekino, in *Int. J. Fatig.*, 2001, 23, pp. 441-448.

[41] W. Yuan, C. Stephens, P. Liaw, L. Shaw, R. A. Buchanan and R. McDaniel, "Fatigue properties of surface nanocrystalline and hardened titanium, presented at the undergraduate poster competition," in *PhD thesis, University of Tennessee,,* March 2003.

[42] K. Dai, J. Villegas, Z. Stone and L. Shaw, in *Acta Mater.*, 2004, 52, p. 5771–5782.

[43] J. W. Tian, J. C. Villegas, W. Yuan, D. Fielden, L. Shaw, P. K. Liaw and D. L. Klarstrom, in *Mater. Sci. Eng. A*, 2007, A468–470, p. 164–170.

[44] A. V. Korznikov, I. M. Safarov, V. P. Pilyugin and R. Z. Valiev, in *Nanostruct. Mater.*, 1994, 4, p. 156–159.

[45] X. Y. Wang and D. Y. Li, in *Electrochim. Acta*, 2002, 47, p. 3939–3947.

[46] F. A. Gao, N. Trannoy and J. Lu, in *Mater. Sci. Eng. A*, 2004, 369, p. 36– 42.

[47] U. M, T. Y and T. K, "Formation of nanocrystalline structure in steels by air blast shot peening," in *Mater. Trans.*, 2003, 44, p. 1488–93.

[48] T. Y, U. M and T. K, "Comparison of Nanocrystalline Surface Layer in Steels Formed by Air Blast and Ultrasonic Shot Peening," in *Mater. Trans.*, 2004, 45, pp. 376-9.

[49] H.-G. S. M, M. A, G. M, G. A and B. M, "The effect of nitriding, severe shot peening and their combination on the fatigue behavior and micro-structure of a low-alloy steel," in *Int. J. Fatigue*, 2014, 62, pp. 67-76.

[50] H.-G. S. M, M. A, G. M and G. A, "Nitriding duration reduction without sacrificing mechanical characteristics and fatigue behavior: The beneficial effect of surface nano-crystallization by prior severe shot peening," in *Mater. des.*, 2014, 55, pp. 492-8.

[51] H.-G. S. M, M. A and G. M, "Fatigue Properties of a Low-Alloy Steel with a Nano-Structured Surface Layer Obtained by Severe Mechanical Treatments," in *Key Eng. Mater.*, 2013, pp. 577-578; 469–72 .

[52] S. M. Hassani-Gangaraj, A. Moridi and M. Guagliano, "From conventional to severe shot peening to generate nanostructured surface layer: A numerical study," in *6th International Conference on Nanomaterials by Severe Plastic Deformation*, 2014, 63.

[53] J. Badreddine, M. Micoulautc, S. Remyb, E. Rouhaudb, P. Renaudd, C. F. and V. Desfontainea, "A model for ultrasonic shot peening: optimization of chamber design in an industrial context," 2014.

[54] K. Funatani and G. E. Totten, "Heat Treating," ASM International, 2001, p. 385.

[55] MITSUBISHI HEAVY INDUSTRIES, LTD., "RESIDUAL STRESS IMPROVEMENT FOR NICKEL BASED ALLOY PWSCC MITIGATION BY ULTRASONIC SHOT PEENING," *EJAM,* Vols. 1, No.3.

[56] J. R. Groza and J. F. Shackelford, in *Materials Processing Handbook,* CRC Press, 2007, pp. 31-32.

[57] Sonats, [Online]. Available: http://www.sonats-et.com/page_38-applications-by-sectors.html.

[58] Sonats, [Online]. Available: http://www.sonats-et.com/page_14-stressonic-principle.html.

[59] K. Lu and J. Lu, "Nanostructured surface layer on metallic materials induced by surface mechanical attrition treatment," *Materials Science and Engineering,* p. 38–45, 2004.

[60] B. Bay, N. Hansen, D. Hughes and D. Kuhlmann-Wilsdorf, *Acta Metall. Mater. 40,* p. 205, 1992.

[61] J. Badreddine, D. Gallitelli, E. Rouhaud, M. Micoulaut, S. Remy, M. François, V. Desfontaine, F. Chateau, P. Renaud and G. Doubre-Baboeuf, "COMPLETE SIMULATION OF ULTRASONIC SHOT PEENING PROCESS," *Surface Modification Technologies,* 2012.

[62] M. Micoulaut, D. Retraint, P. Viot and M. Francois, "HETEROGENEOUS ULTRASONIC SHOT PEENING : EXPERIMENT AND SIMULATION".

[63] C. Nouguier-Lehon, M. Zarwel, C. Diviani, D. Hertz, H. Zahouana and T. Hoc, "Surface impact analysis in shot peening process," 2013.

[64] J. Badreddine, E. Rouhaud, M. Micoulaut and S. Remy, "Simulation ofshotdynamicsforultrasonicshotpeening: Effects

ofprocessparameters," *International Journal of Mechanical Sciences,* 2014.

[65] J. Badreddine, M. Micoulaut, E. Rouhaud, D. Retraint, M. Francois and S. Remy, "Impact velocity and distribution in ultrasonic shot peening," 2011.

[66] J. Badreddine, M. Micoulaut, E. Rouhaud, S. Remy, D. Retraint and M. François, "Effect of the confinement on the properties of ultrasonic vibrated granular gases," 2013.

[67] M. Micoulaut, S. Mechkov, D. Retraint, P. Viot and M. François, "Granular gases in mechanical engineering: on the origin of heterogeneous ultrasonic shot peening," 2007.

[68] J. Marteau, M.Bigerelle, P.-E.Mazeran and S.Bouvier, "Relation between roughness and processing conditions of AISI 316L stainless steel treated by ultrasonic shot peening," *Tribology International,* 2014.

[69] K. Dai and L. Shawb, "Comparison between shot peening and surface nanocrystallization and hardening processes," *Materials Science and Engineering,* 2007.

[70] T. Chaise, J. Li, D. Nelias, R. Kubler, S. Taher and G. Douchet, "Modelling of multiple impacts for the prediction of distortions and residual stresses induced by ultrasonic shot peening (USP)," *Materials Processing Technology,* pp. 2080-2090, 2012.

[71] Y. Todaka, M. Umemoto and K. Tsuchiya, "Comparison of Nanocrystalline Surface Layer in Steels Formed by Air Blast and Ultrasonic Shot Peening," 2004.

[72] Avion Solutions Inc., [Online]. Available: https://www.youtube.com/watch?v=jGM_AEvdi_E.

[73] A. Luo and M. Pekguleryuz, "Cast magnesium alloys for elevated temperature applications," *Mater. Sci,* p. 5259–5271, 1994.

[74] P. Zhang and J. Lindemann, "Influence of shot peening on high cycle fatigue properties of the high-strength wrought magnesium alloy AZ80," *Scr. mater.*, 2005, 52.

[75] W. Liu, J. Dong, P. Zhang, Z. Yao, C. Zhai and W. Ding, "High cycle fatigue behavior of as-extruded ZK60 magnesium alloy," *J. Mater. Sci.* , p. 2916–2924, 2009, 44.

[76] M. S. Bhuiyan, Y. Mutoh and A. McEvily, "The influence of mechanical surface treatments on fatigue behavior of extruded AZ61 magnesium alloy," *Mater. Sci. Eng*, p. 69–75, 2012.

[77] L. Mackenzie and M. Pekguleryuz, "The influences of alloying additions and processing parameters on the rolling microstructures and textures of magnesium alloys," *Mater. Sci. Eng.* , p. 189–197., 2008, A480.

[78] Y. Huang, W. C. Liu and J. Dong, "Surface characteristics and fatigue performance of warm shot peened wrought magnesium alloy Mg–9Gd–2Y," *Materials Science and*, pp. 1481-1487.

[79] Special Metals Corporation, 2007. [Online]. Available: http://www.specialmetals.com/documents/Inconel%20alloy%20718.pdf.

[80] nickelinstitute, "Engineering Properties of Alloy 713C," [Online]. Available: https://www.nickelinstitute.org/~/media/Files/TechnicalLiterature/Alloy713C_337_.ashx.