

Properties Assessment of Perforated Metal Plates for Medical Use

Marija Osipova

Mechanical and Biomedical
Engineering Institute
Riga Technical University
Riga, Latvia
marija.osipova@edu.rtu.lv

Viktors Mironovs

Mechanical and Biomedical
Engineering Institute
Riga Technical University
Riga, Latvia
viktors.mironovs@rtu.lv

Antons Pacejs

Rezekne Academy of Riga Technical
University
Rezekne, Latvia
antons.pacejs@rta.lv

Aleksejs Tatarinovs

Institute of Electronics and Computer
Science
Riga, Latvia
aleksejs.tatarinovs@edi.lv

Jānis Lungevics

Mechanical and Biomedical
Engineering Institute
Riga Technical University
Riga, Latvia
janis.lungevics@rtu.lv

Vjacheslavs Zemchenkovs

Mechanical and Biomedical
Engineering Institute
Riga Technical University
Riga, Latvia
v.zemchenkov@gmail.com

Abstract—Thin-walled and sheet materials with regular through holes (perforation) have wide practical application in various fields, including in medicine for the manufacture of implants, trays for placing and storing cutting instruments, sterilization of consumables. Perforated metal materials (PMM), primarily made of titanium and stainless steel, are of the most attention to specialists in the field of medical engineering, since they are characterized by lower weight, high strength and biomechanical compatibility. The mechanical characteristics of PMM are determined by the initial properties of the material, the dimensions of the sheet or tape, the shape and total area of the perforation. If selected correctly, dimensions and area of the perforations can provide optimal flexibility and plasticity with a significant reduction in the weight of the implant. This paper presents properties of perforated plates made of stainless steel, obtained by non-destructive methods. In particular, the dependences of the Lamb wave velocities at different frequencies on the specific total area of the plate's perforation are shown. The data of elastic properties dependences on the perforation area. The data of microscopic studies of changes in the quality of holes obtained by laser cutting are also presented.

Keywords— implants, laser cutting, non-destructive methods, perforated metal materials.

I. INTRODUCTION

Metallic materials with a perforated structure, with regular or irregular perforations (through-holes), have a wide range of practical applications in medicine. They are used for manufacturing dental implants, trays for storing

and organizing surgical instruments, and for sterilizing disposable medical supplies (Fig. 1) [1] – [3].



Fig. 1. Variations of perforated materials use in medical applications: dental joint implant and sterilization tray.

Metallic materials, such as titanium and stainless steel, are of the high interest to specialists in medical engineering. Those materials are preferred due to their lower weight, high strength, and superior biocompatibility compared to other materials [4], [5]. In implant manufacturing, PMMs provide enhanced strength while maintaining a low weight (Fig. 2).

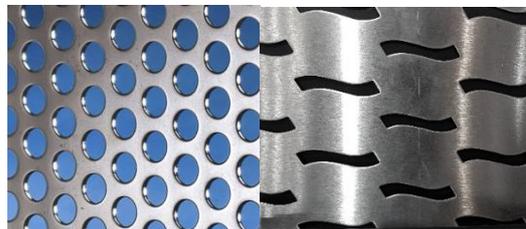


Fig. 2. Types of perforation in metal constructions.

Modern prosthetic limbs are also frequently made from PMMs, which reduces their weight and enhances patient

Online ISSN 2256-070X

<https://doi.org/10.17770/etr2025vol4.8453>

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comfort. Perforation holes vary in size and shape. An important parameter of a product made from perforated material is the total perforation area, as well as the relative arrangement of the holes [6]. Circular perforations provide a high hole density and good ventilation [7], [8]. Studies show that perforation parameters significantly affect the mechanical properties of perforated elements [9]. It has been established that implants with high mechanical strength bear most of the load, leading to atrophy of the surrounding bone tissue and a decrease in its density around the implant, a phenomenon known as stress shielding effects [10] – [13]. Therefore, it is crucial to reduce the elastic properties, such as Young’s modulus of materials and elements used in orthopaedic implants [3]. PMMs with Young’s modulus close to the elastic-plastic properties of human bone (Young’s modulus: 10–30 GPa, depending on the bone type) ensure better load distribution between the implant and the surrounding bone, reducing stress shielding effects and ensure better load distribution between the orthopaedic implant and the bone, reducing the risk of bone degradation [14], [15]. Effective control of these properties through material selection and manufacturing technologies, such as the use of alloys with modified microstructures, porous or powder-based material structures, and the application of PMMs, enhances osteointegration and improves implant functionality [10], [11]. Various technological methods are used for manufacturing PMMs, including stamping, waterjet cutting, plasma cutting, and laser cutting [16], [17]. Laser cutting enables the production of components with more complex perforation patterns and smaller hole sizes [6]. In this process, which is used for manufacturing medical devices, important factors include surface roughness and deviations in hole profile.

II. MATERIALS AND METHODS

For experimental studies, plates made of stainless steel SS304 were manufactured using the laser cutting method (Fig. 3). The main objective of this work was to investigate the properties of perforated steel plates, including elastic properties, perforation accuracy, and ultrasound propagation velocities, in order to determine the impact of perforations on these characteristics.

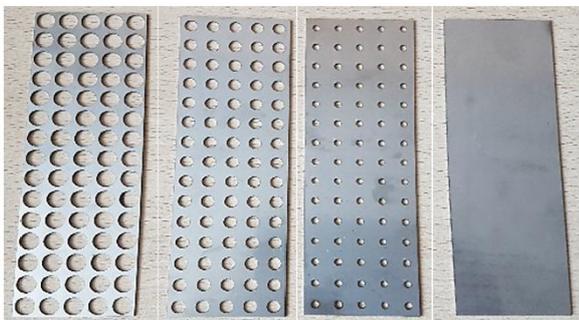


Fig. 3. Perforated stainless steel SS304 plates. Length: 140 mm, width: 25 mm, thickness: 1 mm. Hole diameter: 3 to 8 mm. Total perforation area: 0% to 50%.

A. Elastic properties determination.

The determination of the elastic properties of perforated metal plates was conducted through non-destructive methods, laser vibrometry using the Polytec PSV-500 system. Laser vibrometry is a method of determining the dynamic properties of the sample - the resonant frequencies, which in turn are needed to determine the elastic properties [18] – [20]. In the control software, the excitation frequency range was configured from 0 to 10 kHz, encompassing the resonance frequencies of the plates. The surface of each plate was systematically scanned along its length and width to capture a detailed representation of its vibrations. The obtained resonance frequency values were used in the corresponding equations to determine the Young’s modulus of the plates. Each perforated stainless steel SS304 sample underwent testing using the laser vibrometry method. Following each test, the fundamental bending frequency was recorded. Table 1 presents the collected data on the fundamental bending frequencies for all tested samples. The Young’s modulus E of the samples was calculated using the fundamental bending frequency f_b with the following formula:

$$E = 0.9465 \times m \times \frac{f_b^2}{b} \times \left(\frac{l}{h}\right)^3 \times T \quad (1)$$

where the geometric parameters required for calculating the Young’s modulus of the tested samples included thickness h , length l , and width b , while the physical parameter considered was mass (m). The correction factor T (applicable for $l/h > 20$) was computed using the following equation:

$$T = 1 + 6.585 \left(\frac{h}{l}\right)^2 \quad (2)$$

Young’s modulus E of the tested samples was determined using experimentally obtained fundamental bending frequencies, applying the equations (1) and (2) as referenced in [21], [22]. For these calculations, key geometric parameters, including length, width, and thickness — were precisely measured with a caliper, while the sample weight was recorded using a scale. The data used for calculating Young’s modulus of perforated stainless steel 304 plates are presented in Table 1.

TABLE I. Physical, geometric, experimental, and computed data of perforated stainless steel SS304L samples.

Sample №	Weight (g)	Fundamental bending frequency (kHz)	Correction factor T	Perforated plates Young’s modulus (GPa)
1	57.838	236.875	1.000293	207.6171
2	53.690	226.75	1.000293	176.4166
3	43.634	207.875	1.000293	120.4983
4	27.687	178.375	1.000293	56.2987

B. Lamb wave velocities at different frequencies determination.

Ultrasonic measurements were carried out using the surface profiling method using a pair of transducers, a transmitter and a receiver. One of the transducers was fixed on the surface of the plate, and the other moved linearly along the surface, with the ultrasonic signals being recorded step by step. The propagation velocity of the ultrasonic wave was measured by the shift of the first extremum of the received signal and calculated as a linear approximation of the ratio of the increment in the distance between the transducers to the increment in time. The measurements were carried out using three pairs of transducers with operating frequencies of 60, 150 and 450 kHz. To amplify the signal at a given operating frequency of the emitter, the excitation pulse was a 2-period toneburst at this carrier frequency. To weaken the reflected signals from the ends of the plates and prevent their interference with the direct propagation signal, the plates were dampened at the ends with plasticine. Silicone-based acoustic gel was used as contact lubricant.

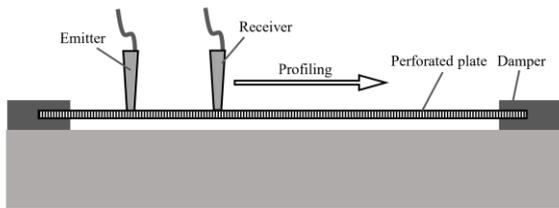


Fig. 4. Layout of ultrasonic measurements on the perforated plate.

C. Accuracy of the perforation determination.

To assess the accuracy of the perforations, equipment from the Japanese company MITUTOYO was used. Profile evaluation was also conducted through macro- and microscopic analysis. The Quick Vision QV-X302T1L-E optical measurement system was employed to assess the diameter deviation of perforations in SS304 stainless steel plates. The perforations, with nominal diameters of 3 mm, 5.5 mm, and 8 mm, were measured using the system's high-resolution camera and advanced image processing software. The measurement procedure involved placing the perforated plate on the motorized stage of the Quick Vision system. The stage was adjusted to align the perforations with the camera's field of view. The system's autofocus function was utilized to ensure sharp imaging of the perforation edges. For each perforation, the diameter was measured at multiple points along the circumference to account for potential ellipticity or irregularity. The software calculated the average diameter and compared it to the nominal diameter, determining the deviation. The results were recorded with a resolution of 0.1 μm . The Quick Vision QV-X302T1L-E system provided repeatable and

precise measurements, enabling the quantification of diameter deviations for quality control and compliance with specified tolerances (Fig. 5). The data were exported for further statistical analysis to evaluate the consistency of perforation dimensions across the plates.

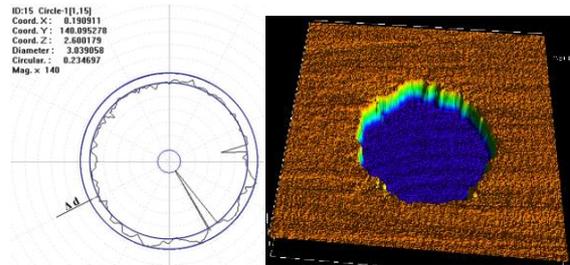


Fig. 5. Perforation profile with 3 mm diameter in SS304 steel plate and enlarged perforation 3D profile.

III. RESULTS AND DISCUSSION

A. Elastic properties measurements.

On Figure 3 is shown a plot, that presents the dependence of Young's modulus of perforated stainless steel SS304 plates on the perforation area for plates. The plot indicates a decrease in Young's modulus of perforated plates as the perforation area increases.

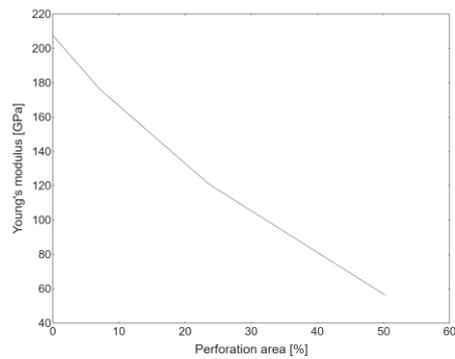


Fig. 6. Dependence of Young's modulus of perforated SS304 stainless steel plates on perforation (perforated plates dimensions of Length: 140 mm, width: 25 mm, thickness: 1 mm. Hole diameter: 3 to 8 mm. Total perforation area: 0% to 50%).

As the perforation area is 0%, the Young's modulus of perforated plate is 207.617 GPa. With an increase of perforation area to 7.07 %, the decreasing trend continues, and the Young's modulus of perforated plate reaches 176.417 GPa. When the perforation area increases to 23.76 %, the Young's modulus of perforated plate decreases further to 120.498 GPa. The most significant reduction in all parameters occurs at a perforation area of 50.27 %, where the Young's modulus of perforated plate falls to 56.299 GPa. Summarizing the Young's modulus there is a

gradual decrease in Young’s modulus (about a 151.318 GPa difference). Considering the Young’s modulus of human bone, which ranges from 10 to 30 GPa, the sample with the highest perforation area 50.27 %, has a Young’s modulus of perforated plate is 56.299 GPa, which is still higher than the Young’s modulus of human bone. Therefore, further research into SS304 stainless steel plates with perforation areas greater than 50.27 % would be necessary to reduce the Young’s modulus closer to that of human bone.

B. Ultrasonic measurements.

Using surface profiling of plates, we obtained ultrasound propagation velocities in the range from 1080 to 2800 m/s. This is several times lower than the velocity of the longitudinal wave in steel, where its tabular value is about 6300 m/s in volume. In addition, a pronounced dependence of the velocity on frequency was obtained. From this we concluded that the measured values of the velocity refer to an asymmetrical zero-order Lamb wave or a flexural wave. For this wave, the propagation velocity depends on the ratio of the plate thickness to the ultrasonic wavelength, and therefore, for the same plate thickness, on the frequency.

As the degree of perforation increased from 0 to 50.27 %, the velocity of the flexural wave decreased consistently. Figure 7 illustrates the dual dependence of the ultrasound velocity on both the frequency and the degree of perforation.

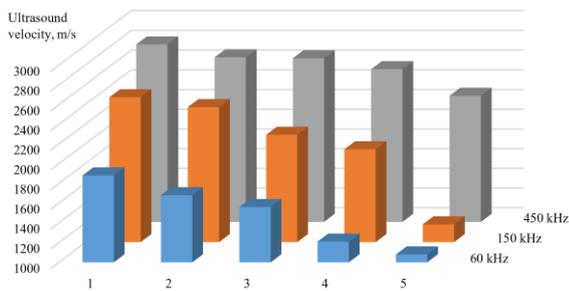


Fig. 7. Changes in ultrasound velocity in perforated plates depending on the specific degree of perforation (1 - 0; 2 - 7.1%, 3 - 12.6%, 4 - 23.8%, 5 - 50.3%) for three ultrasound frequencies (60, 150 and 450 kHz).

At the same time, the degree of dependencies is different at different frequencies and at different sections of perforation increment. So, at a high frequency of 450 kHz, the graph of the speed dependence on the degree of perforation is flat, at a low frequency of 60 kHz it is steep, and at an intermediate frequency of 150 kHz it is flat at a low degree of perforation and steep at a high degree. This can be explained by the fact that at high frequency the ultrasonic wave tends to bypass the perforation and spread over a solid area, while at low frequency it makes the plate vibrate. Thus, the ultrasound velocities at different frequencies can be used as indicators of the properties of

the plate material and the integral rigidity of the plate, considering the perforation. By applying advanced data analysis methods in the future and larger databases, it becomes possible to differentially evaluate the factors of plate thickness, its material properties and the degree of perforation.

C. Perforations accuracy measurements.

Measurements of the hole profile in steel plates produced by laser cutting revealed a slight increase in profile deviations as the hole diameter increased. At the same time, no changes in hole profile deviations along the length of the plate were observed. Figure 8 illustrates the variation in circularity of perforations along the length of SS304 stainless steel plates for three different hole diameters (3 mm, 5.5 mm, and 8 mm). The x-axis represents the plate length (0 to 140 mm), while the y-axis shows the circularity of the perforations. The results indicate that for 3 mm perforations, circularity fluctuates significantly along the plate length, with values ranging from 0.06 to 0.14, suggesting greater variability in profile accuracy. In contrast, 5.5 mm and 8 mm perforations exhibit more stable circularity values, remaining within a narrower range (approximately 0.035 to 0.06). The lower circularity deviations in larger perforations indicate improved hole profile consistency. A notable trend is the higher circularity variability for 3 mm perforations, particularly at the beginning and end of the plate. This could be attributed to process-related effects such as thermal influence, laser power fluctuations, or cutting path instabilities. The 5.5 mm and 8 mm perforations remain relatively stable along the entire plate length, indicating that larger holes maintain better geometric precision.

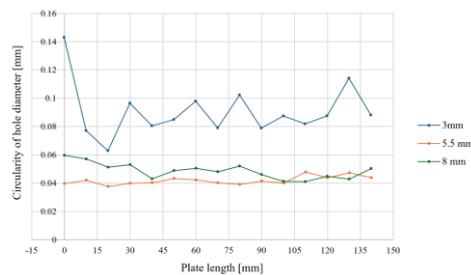


Fig. 8. Dependence of circularity of perforated SS304 stainless steel plates on plate length (perforated plates dimensions - length: 140 mm, width: 25 mm, thickness: 1 mm. Hole diameter: 3 to 8 mm).

This data indicate that increasing the perforation area in stainless steel plates significantly alters their mechanical and acoustic properties. However, it should be noted that the study was limited to a specific material (SS304) and a particular range of perforation areas. Further research is needed to assess whether similar trends occur in titanium-based or other biomedical alloys. Previous studies have primarily focused on the mechanical properties of metal constructions with circular holes, in civil engineering

applications, while their potential for medical use remained largely understudied [23]. This work presents a comparative analysis of key elastic parameters for perforated metal constructions, for medical orthopedic implants, to decrease the stress-shielding effect.

CONCLUSIONS

The study investigated the properties of perforated stainless steel SS304 plates, focusing on their elastic properties, perforation accuracy, and ultrasound propagation velocities. Using non-destructive methods, including laser vibrometry, the research determined that the Young's modulus of the plates decreases as the perforation area increases, with a significant reduction observed at a 50.27 % perforation area. This reduction in Young's modulus suggests potential for better load distribution in medical implants, reducing stress shielding effects.

Additionally, the study found that ultrasound velocity related to the propagation of Lamb wave in plate decreases with increased perforation, indicating changes in the entire rigidity of the plate under the influence of perforation.

The accuracy of perforations was assessed, revealing that medium-sized holes (5.5 mm) have the most stable circularity, while smaller and larger holes show higher deviations.

ACKNOWLEDGMENTS

This work has been supported by the Latvian Council of Science LZP FLPP no. LZP -2021/1-0290, Comprehensive assessment of the condition of bone and muscle tissue using quantitative ultrasound (BoMUS)". We would like to thank students A. Sirotkina (Riga Technical University) for active participation.

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