Rastislav R. Nigrovič
University of Žilina
Faculty of Mechanical Engineering,
Slovakia

Jozef Meško
University of Žilina
Faculty of Mechanical Engineering,
Slovakia

Ružica R. Nikolić
University of Kragujevac
Faculty of Engineering
and
University of Žilina
Research Center,
Slovakia

Vukić Lazić
University of Kragujevac
Faculty Engineering

Dušan Arsić
University of Kragujevac
Faculty of Engineering

Branislav Hadzima
University of Žilina
Research Center,
Slovakia

Comparison of the PMMA mechanical properties after cutting by the laser beam and milling

This research was focused on characterization of the influence of laser cutting on the material made from the PMMA. The comparison of mechanical properties of samples cut by the laser beam to the properties, obtained after the conventional method of cutting by milling, are presented in this paper, as well. The 4 mm thick samples were prepared from the PMMA and subjected to tensile test to establish their material strength after the two different types of cutting. Samples that were cut by the laser beam were also subjected to tempering to improve their mechanical properties. It was concluded that the way of cutting has a strong influence on the PMMA samples mechanical properties. The outcome of the experiment is a direct assessment of roughness of the cut samples. It is shown that the laser cutting produces lower values of the surface roughness. However, for manufacturing the structural elements, the more suitable would be application of the milling technology since it results in better mechanical properties of the cut sample.

Keywords: *laser cutting, milling, PMMA, mechanical properties, surface roughness.*

1. INTRODUCTION

The laser cutting of metallic and non-metallic materials is based on the focused laser beam action on the material being cut. In technical practice, the surface of the material is impacted by a focused circular laser beam of a diameter 0.1 to 0.4 mm. The size of the beam diameter depends on the thickness of the cut material, as well as on the construction of the device for the laser beam cutting. When the laser beam, of the above parameters, impacts the material being cut it causes the material's rapid heating up. Within milliseconds, the material is heated up to the melting or the evaporation temperature [1-6].

When the laser beam hits the material that is being cut, an interaction occurs between the material and the laser beam. The subsequent processes, which take place during the cutting of the material, and the effect on the material properties following the focused beam impact, mainly depend on the chemical composition of the material being cut and on the quality of its surface, as well [4, 7-11].

In thermal cutting by a laser, it is always necessary first to create a hole in the processed material. Then the actual cutting is continued from that hole. Making the hole is based on the laser drilling principle. That process has slightly different characteristics with respect to the cutting itself. The impacting laser beam transmits the kinetic energy of the material photons, which is converted into heat that melts and partially evaporates the material being heated. The surroundings of the laser beam inflammation site (in the material being cut) contain gases that are ionized instantaneously as the beam hits the material and change to plasma. The material being cut sublimates into a gaseous state and gets blown away to the environment by the action of an assist gas under a relatively high pressure. The part of the material, which is not converted into a gaseous state, is blown away in the liquid form by the flowing assist gas. The above-described process causes formation of a pit in the cut material and thus the laser beam can penetrate continuously deeper, which results in depth melting of the material, [1, 3, 11-12].

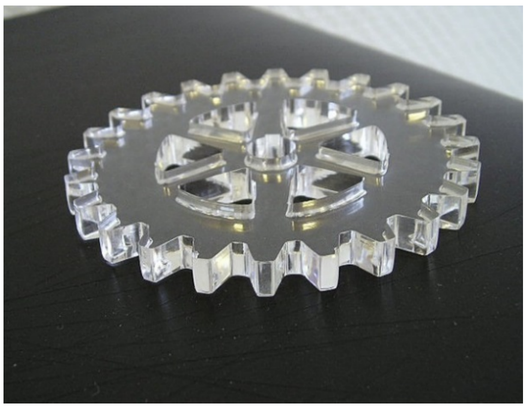

Figure 1. Example of the PMMA product for laser cutting

The CO_2 lasers are particularly well suited to the cutting of the PMMA. Applications of thermoplastic PMMA have grown considerably in many cases, for example, lenses, light pipes, outdoor signs, light covers, bathroom fittings, skylights, meter covers, baths and toys [11].

Received: February 2017, Accepted: July 2017
Correspondence to: Rastislav R. Nigrovič
University of Žilina, Faculty of Mechanical Engineering, Žilina. Slovak Republic
E-mail: rastislav.nigrovic@fstroj.uniza.sk
doi:10.5937/fmet1801057N

2. EXPERIMENTAL INVESTIGATIONS AND DISCUSSION OF RESULTS

2.1 Machines and equipment

The milling machine – GERBER Sabre 408 was used in experiments, with the following cutting parameters: tool diameter – ø 4 mm; operating speed – 22 000 RPM; milling speed – 36 mms^{-1}.

The laser cutting and engraving machine – XL 1200 was used for the second type of cutting. The EUROLASER offers the possibility to process extremely large samples on a comparatively small system. The processing area is 2270 mm x 1230 mm. With the optional camera recognition system, which is also available for other systems, the production flow can be automated, leading to an increased economy of the laser processing [13].

The laser beam cutting was done with the following parameters: power – 100 W; cutting speed – 13 mms-1.

The PMMA milling schematics is shown in Figure 2 and the laser beam cutting in Figure 3.

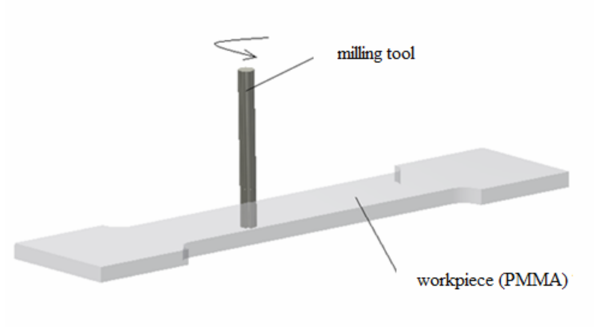

Figure 2. Scheme of the PMMA milling

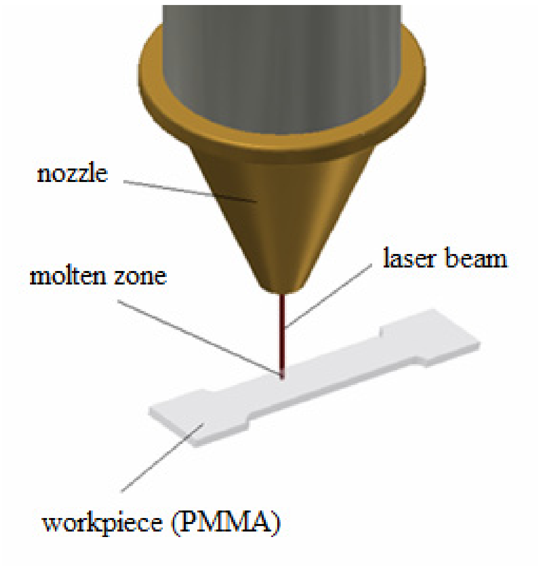

Figure 3. Scheme of the PMMA laser cutting

2.2 The material

General Polymethacrylates are polymers of the esters of methacrylic acids. The most commonly used among them is polymethyl metacrylate - PMMA. Polymethyl metacrylate or polymethyl 2–methylpropenoate is the polymer of methyl methacrylate, with chemical formula $C_5H_8O_2$. It is a clear colorless polymer available on the market in both pellet and sheet form under the names Plexiglas, Acrylate, Perspex, Playcryl, Acylplast, Altuglas, Lucite etc. It is commonly called acrylic glass or simply acrylic, [14].

2.3 Measurements of the maximum strength

In this experiment, the influence of the laser beam and the milling tool on the integrity and mechanical properties of the material was evaluated by measuring the strength of the PMMA. The samples were subjected to tensile test to determine the impact of the character and integrity of the cutting edge after laser cutting and milling. Further, the laser cut samples were dried for 5 h at 70 °C.

Table 1. The physical, mechanical and thermal properties of PMMA [13]

Density	1.15-1.19 gcm^{-3}
Water absorption	0.3 – 2 %
Hardness, Rockwell M	63 – 97
Tensile Strength, Ultimate	47-49 MPa
Tensile Modulus	2.2 – 3.8 MPa
Specific Heat Capacity	1.46 – 1.47 J/g ºC
Thermal Conductivity	0.19-0.24 W/mK
Maximum Service Temperature, Air	41 – 103 [ºC]
Melting Point	130 ºC
Vicat Softening Point	47 – 117 ºC
Glass Temperature	100 – 105 ºC

Table 2. Tensile test results for samples from PMMA

Sample #	Laser cutting	Laser cutting – dried	Milling
1	35.65	42.86	57.12
2	39.04	38.42	49.97
3	34.44	41.52	43.99
4	32.50	39.50	60.98
Average maximum strength R_m (MPa)	35.4075	40.57	53.015

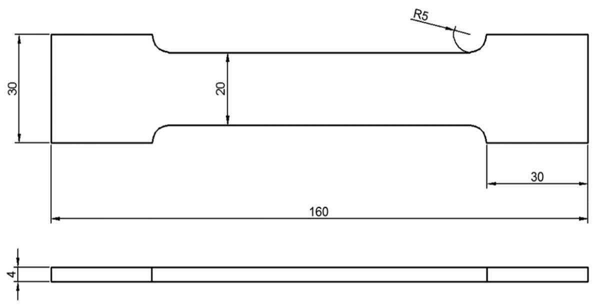

Figure 4. Sketch of the comparative sample for tensile test

The samples, which were milled had the average strength of 53.015 MPa and samples from laser cutting 35.405 MPa, which means that the former samples (of 4 mm thickness and 20 mm width) had about 1.5 times higher tensile strength Rm than the latter, Table 2. These useful features make it ideal for use in demanding conditions. The laser cut samples were further additionally dried in a tempering oven at 70 °C for 5 h. However, that prolongs the time-consumption for production of parts cut by the laser beam, though it was almost 3 times faster (13 mms-1), compared to 36 mms-1 for milling. After the additional drying in tempering furnace, samples had the tensile strength of 40.57 MPa.

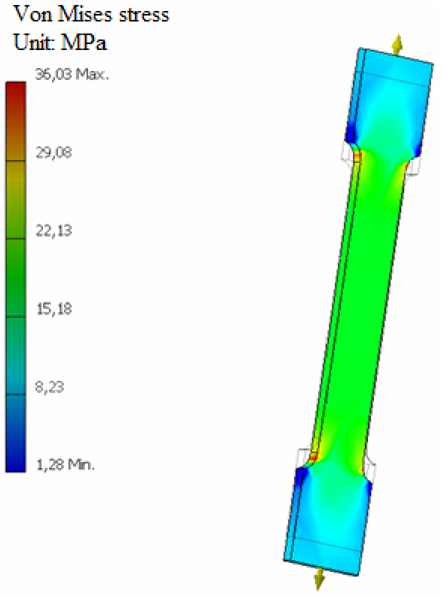

Figure 5. Simulation tests of tensile strength

2.4 Measurements of the HAZ width

During the laser beam cutting, the heat-affected zone (HAZ) appears in the PMMA samples. The measured values of the HAZ width are shown in Table 3, for both cases of the PMMA cutting, i.e. with and without additional drying. Appearance of the HAZ and the base material (BM) microstructures are shown in Figures 6 and 7, while in Figure 8 is presented the appearance of the surface after milling.

Table. 3. The PMMA HAZ width measurements (μm)

Sample #	Laser cutting	Laser cutting - dried	Milling
1	81.80	82.10	0
2	82.10	80.80	0
3	80.50	82.30	0
4	80.50	80.30	0
5	82.30	79.60	0
Average	81.44	81.02	0

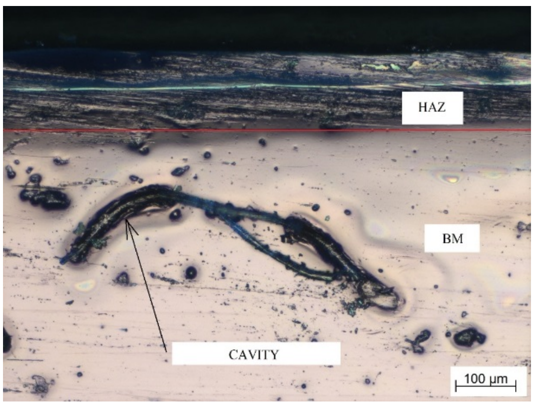

Figure 6. The HAZ and BM microstructures obtained by the laser cutting without drying

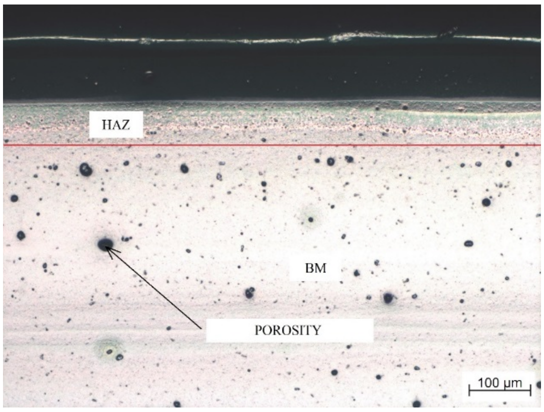

Figure 7. The HAZ and BM microstructures obtained by the laser cutting after drying

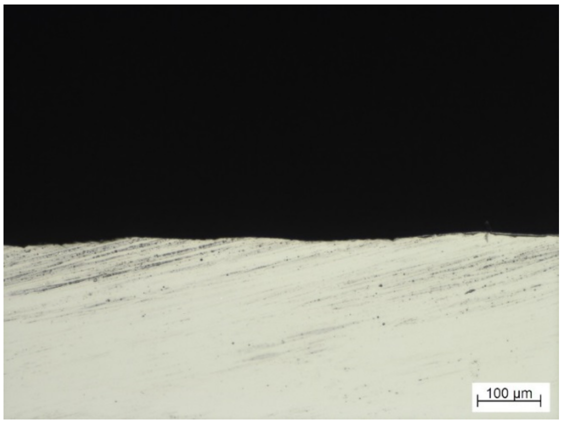

Figure 8. Surface and microstructure after milling

From the measurements of the HAZ size and appearance of its microstructure, one can conclude that the tensile strength of the material was reduced due to the appearance of cavities in the material just below the HAZ. On a small scale, those faults can be remedied by drying of the PMMA samples, which causes increase of the tensile strength, since the cavities sizes were reduced and the pores were regularly spaced. The width of the HAZ was not substantially changed after the samples drying. The heat-affected zone (HAZ) was not present in samples that were prepared by milling.

3. INVESTIGATION OF THE SURFACE ROUGHNESS INFLUENCE ON MAXIMUM TENSILE STRENGTH

The roughness of the cut surface was measured to establish if it imposes any influence on the material's maximum tensile strength. For the PMMA samples cut by milling the average surface roughness was $R_z = 21.9$ μm, while for the laser-beam cut samples it was $R_z = 1.1$ μm. From those data, it can be easily concluded that the surface roughness has no effect on the material's maximum tensile strength; roughness was much bigger for the samples obtained by milling, which had significantly higher maximum tensile strength. The only "influence" of the surface roughness is in optical appearance, since the surfaces obtained by the laser beam cutting looks smoother.

Images of the cut area surface geometry of experi–mental samples made of PMMA, obtained by laser cutting and by milling are shown in Figures 9 and 10, respectively.

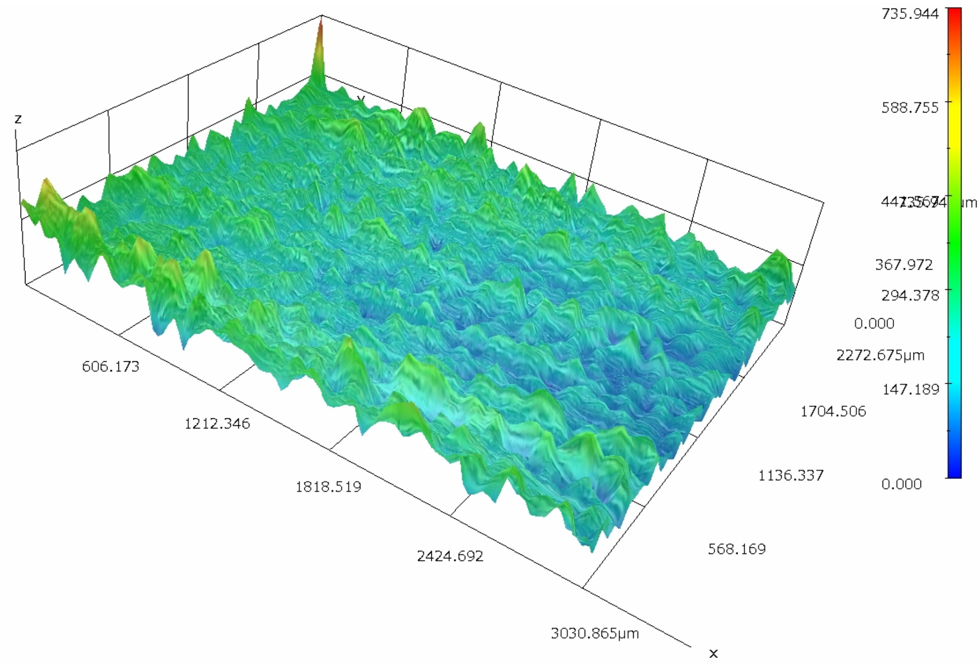

Figure 9. Image of the cut area surface geometry of a PMMA sample obtained by laser cutting

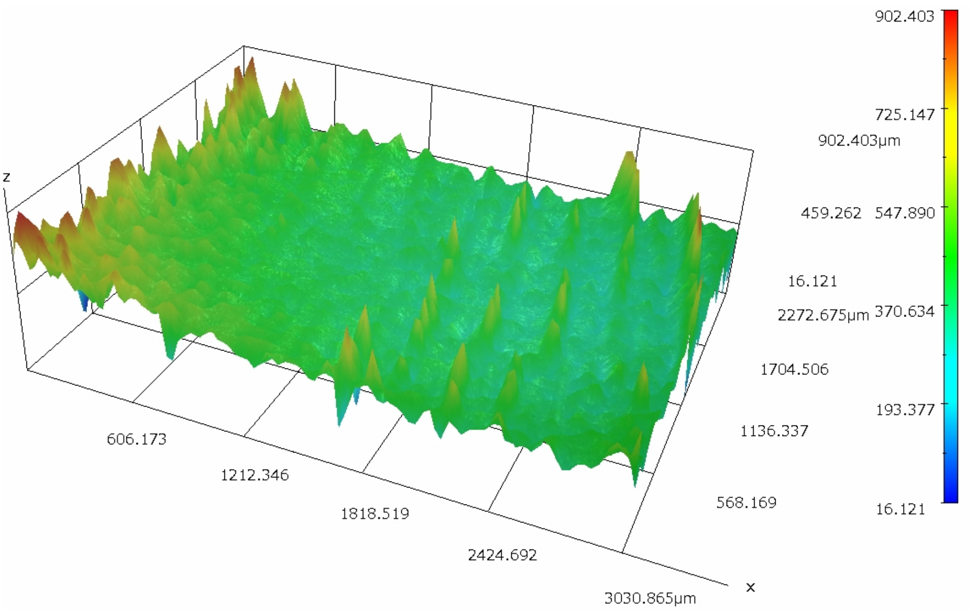

Figure 10. Image of the cut area surface geometry of a PMMA sample obtained by milling

4. CONCLUSIONS

The paper describes the principle of the laser cutting of plastics, in particular the PMMA, and the impact of the laser beam on the material and its ability to be cut. The PMMA is a specific type of plastic material that can be laser cut. Therefore, this type of material was consi–dered from the viewpoint of its mechanical properties.

The PMMA samples were treated in three different ways – by milling and the laser beam cutting with and without drying. It was concluded that the type of cutting has the strong influence on material's mechanical proper–ties, namely the tensile strength. It was significantly lo–wer for samples cut by the laser beam with respect to that of samples obtained by milling. It was also confirmed that this reduction in tensile strength is caused by appea–rance of cavities in the material just below the heat-affec–ted zone, created due to heating during the laser cutting.

The HAZ width was also measured for samples cut by the laser beam. It was concluded that drying of the samples does not contribute to narrowing the HAZ. The HAZ was not present in samples obtained by milling.

The surface roughness of the cut surfaces did not impose any influence on the material's maximum tensile strength. It was significantly bigger for the PMMA samples obtained by milling, 21.1 µm (versus 1.1 µm for the samples obtained by laser cutting), which, on the other hand, had the maximum tensile strength signi–ficantly bigger as well.

ACKNOWLEDGMENT

The research presented in this paper was partially financially supported through realization of project VEGA no. 1/0186/09-(V-13-013-00) and Slovak state budget by the Project "Research Centre of the

University of Žilina" - ITMS 26220220183 "Research Centre of the University of Žilina" and by the Ministry of Education, Science and Technological Development of Republic of Serbia through grants TR35024 and ON174004.

Note: *The shorter version of this research was presented at the The 8th International Scientific and Expert Conference "TEAM 2016", reference [15].*

REFERENCES

[1] Silvfast, W. T.: *Laser Fundamentals*, Cambridge University Press, Cambridge, 2004.

[2] Caristan, L. C.: *Laser cutting guide for manufacturing*, Society of Manufacturing Engineers, Dearborn, Michigan, 2004.

[3] Konar, R., Mician, M., Hlavaty, I.: Defect detection in pipelines during operation using Magnetic Flux Leakage and Phased Array ultrasonic method, Manufacturing Technology, Vol. 14, No. 3, pp. 337-341, 2014.

[4] Konar, R., Mician, M.: Non-destructive testing of welds in gas pipelines repairs with Phased Array ultrasonic technique, Manufacturing Technology, Vol. 14, No. 1, pp. 42-47, 2014.

[5] Radek, N., Mesko, J., Zrak, A.: Technology of laser forming, Manufacturing Technology, Vol. 14, No. 3, pp. 428-431, 2014.

[6] Lago, J., Bokuvka, O., Novy, F.: The weld toe improvement of Domex 700 by laser remelting, in: *Proceedings of The 32nd Danubia - Adria symposium on advances in experimental mechanics*, 22-25.09. 2015, Starý Smokovec, Slovakia, pp. 142-143.

[7] Žmindák, M., Meško, J., Pelagič, Z., Zrak, A.: Finite element analysis of crack growth in pipelines, Manufacturing Technology, Vol. 14, No. 1, pp. 116-122, 2014.

[8] Sejc, P., Bielak, R., Svec, P., Rosko, M.: Computer simulation of heat affected zone during MIG brazing of zinc-coated steel sheets, Kovové materiály - Metallic materials. Vol. 44, No. 4, pp. 225-234, 2006.

[9] Vrzgula, P., Faturik, M., Mician, M.: New inspection technologies for identification of failure in the material and welded joints for area gas industry, Manufacturing Technology, Vol. 14, No. 3, pp. 487-492, 2014.

[10] Patek, M., Konar, R., Sladek, A., Radek, N.: Non-destructive testing of split sleeve welds by the ultrasonic TOFD method, Manufacturing Technology, Vol. 14, No. 3, pp. 403-407, 2014.

[11] Huang, Y., Liu, S., Yang, W., Yu, Ch.: Surface roughness analysis and improvement of PMMA-based microfluidic chip chambers by CO2 laser cutting, Applied surface science, Vol. 256, pp. 1675-1678, 2010.

[12] Mesko, J., Zrak, A., Mulczyk, K., Tofil, S.: Microstructure analysis of welded joints after laser welding, Manufacturing Technology, Vol. 14, No. 3, pp. 355-359. 341, 2014.

[13] EUROLASER. (2015). [accessed on 2016-02-01]. http://www.eurolaser.com/cz/products/laser-systems-for-acrylic/xl-1200-acrylic/>.

[14] Van Krevelen, D. W., te Nijenhuis, K.: *Properties of polymers*, Elsevier Science, 2009.

[15] Nigrovič, R., Meško, J., Nikolić, R. R., Lazić, V., Arsić, D.: Comparison of laser beam cutting and milling of plastics materials made from PMMA focusing on mechanical properties of the material, in: *Proceedings of The 8th International Scientific and Expert Conference TEAM 2016*, 19-21.10.2016, Trnava, Slovakia, pp. 92-98.

ПОРЕЂЕЊЕ МЕХАНИЧКИХ КАРАКТЕРИСТИКА PMMA ПОСЛЕ ЛАСЕРСКОГ РЕЗАЊА И ГЛОДАЊА

Р. Нигрович, Ј. Мешко, Р. Р. Николић, В. Лазић, Д. Арсић, Б. Хадзима

Ово истраживање је фокусирано на карактеризацији утицаја ласерског резања на материјал направљен од PMMA. Такође је приказано и поређење механичких особина узорака добијених ласерским резањем и узорака добијених конвенционалном методом резања – глодањем. Узорци дебљине 4 mm су припремљени од PMMA и подвргнути тесту затезањем да би се установила њихова јачина после два различита типа резања. Узорци добијени ласерским резањем су били подвргнути и темперовању да би се побољшале њихове механичке особине. Закључено је да начин резања има снажан утицај на механичке особине узорака од PMMA. Резултат експеримента је и директно процењивање храпавости површина исечених узорака. Показано је да ласерско резање производи мање вредности површинске храпавости. Међутим, за производњу елемената конструкција је повољнија примена технологије глодања, пошто она резултира бољим механичким особинама резаних узорака.