Journal of Physics: Conference Series

PAPER • OPEN ACCESS

The Effect of Laser Beam on the Width of the Cut

To cite this article: J Knedlová *et al* 2024 *J. Phys.: Conf. Ser.* **2712** 012019

The Effect of Laser Beam on the Width of the Cut

J Knedlová[1], M Kubišová[1], V Pata[1], M Marcaník[1] and B Bočáková[2]

[1]Tomas Bata University in Zlín, Vavrečkova 5669, Zlín, Czechia
[2]Slovak University of Technology in Bratislava, Jána Botu 2781/25, Trnava, Slovakia

E-mail: knedlova@utb.cz

Abstract. Conventional methods of dividing material due to their limitation to straight cuts have largely been replaced by non-conventional cutting methods, which include laser cutting. Laser cutting of polymer materials has become a priority for the manufacturing industry, mainly due to the constantly growing demand for these materials. The article discusses the effect of the laser beam on the width of the cut using lenses with different focal lengths, under different working conditions, on samples made of PMMA polymer material plates. For the experiment, the samples were produced using an ILS 3NM laser device, a CO_2, with a wavelength of 10.6 μm and with maximum power 100 W, maximum feed speed 1524 $mm \cdot s^{-1}$. For the selected samples, it was studied how the dimension defined by the machining software differ from the dimension created by the machining.

1. Introduction

Laser technologies are gradually replacing the final methods of material processing in various areas of industry. It has many advantages; it is a technique that is non-contact with the machine. The reason for this is their accuracy, low operating costs without consumables, such as easy maintenance and long service life, which conventional machining methods usually cannot offer. LBM technology achieves high precision, low heat zone, high speed, flexibility, versatility and easy automation and control by computer, in addition to short processing times. Laser machining of materials is influenced by a few different factors. The result of the optimization process is to evaluate the influence of individual factors, emphasize the main ones, neglect the less important and generally be able to set the laser parameters so that the utility values of the product are maximized. The quality of the workpiece depends on the properties of the surface to be machined, on its shape and dimensional accuracy, and on the properties determined by the material and its processing. At the same time, these changes can relate to the future function of the finished area and use them to evaluate the quality of its integrity. The concept of surface integrity (technological inheritance) is very complex, simply put, it is a certain set of characteristics that summarizes the functional properties of the surface. Among the most important are surface topography, structural, physical, and chemical changes in the surface, the degree, depth and character of hardening, the sense, magnitude, and course of residual stresses. [1-2]

There are many types of lasers that are used in the industry for engraving and marking, such as Q - switched Nd: YAG laser, CO_2 laser, excimer laser, semiconductor laser and fiber laser [2]. CO_2 is the most powerful and advantageous gas laser for etching organic materials such as polymers, which are poor conductors of temperature and electricity, also its wavelength of 10.6 μm the laser can easily absorb most organic substances that absorb 10 μm wavelength [3]. The CO_2 laser appears to be an effective technique for machining poly-methyl-methacrylate (PMMA) due to the good absorption of the PMMA laser beam. Polymethylmethacrylate (PMMA) has attracted significant attention in the last decade due to its wide range of applications replacing metal and wood. PMMA, and has been produced at a lower cost for its satisfactory properties [4-6]. The level of accuracy of the shape depends on the ability to remove a thin layer of material on the laser, the engraving process, the removal rate of the material and the quality of the surface completely depend on the material, the properties of the laser source and the process parameters [7]. Therefore, it has become important to optimize the selection of process parameters such as wavelength, scanning speed, power and parallel or step overlap [8-9]. There are many previous works that have been done to optimize laser engraving using different lasers, different material, and other parameters [7-12].

Consequently, this offers the possibility of streamlining the LBM cutting process, eliminating negative phenomena and thus the possibility of making better machined surfaces.

This fact has prompted an effort to experimentally verify the possibility of laser technology of photon cutting of various polymeric materials in connection with the ever-increasing requirements for the quality of final products, but at the same time it is necessary to monitor what the dimension of the final work-piece will be in connection with this technology, how it will differ from the dimension defined for machining by the software.

As an example, the connection of a camera housing from PMMA embedded in the LBM canopy bracket groove, see Figure 1, which could be achieved by defining the exact size of the circular groove without the use of glue, which had a negative effect on the functional properties of the camera housing. A silicone sealant was sufficient protection against the ingress of dirt and sewage water from sewage pipe.

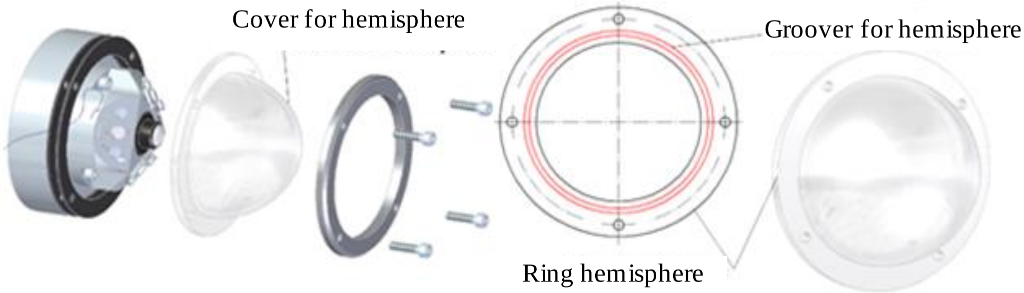

Figure 1. Camera cover.

2. Sample preparation

Machining was preceded by a design of working conditions for the production of samples, from material PMMA, using ILS 3NM, CO_2 device laser having a wavelength $\lambda = 10.6$ μm and with a maximum power $P = 100$ W, maximum cutting speed $v_f = 1524$ mm·s^{-1}.

The main requirement was to penetrate the laser beam through a board with a thickness of 3 mm and 5 mm. Due to the small maximum power of the laser device and material used, reducing the power would not have the desired effect. The pulse value per inch was the same in all cases, namely a PPI of 1000. High power and slow feed rate were prerequisites for cutting, using lenses with focal lengths of 1.5 "(38.1 mm), 2.5" (63.5 mm) and 5" (127.0 mm).

2.1 Testing applicable cutting speeds

Using a lens with a focal length of 1.5 "(38.1 mm), a board with thickness of 3 mm was cut through all selected speeds, a board with a thickness of 5 mm was cut at speed of 45.72 mm·s^{-1} (3%), see Table 1. At slower speeds, there were extreme conditions that caused the PMMA material to degrade due to burning.

Using a lens with a focal length of 2.5 " (63.5 mm), similar effects of cutting conditions were tracked as when using a lens with a focal length of 1.5 " (38.1 mm). For a semi-finished product with a thickness of 3 mm, cutting speeds of 15.24 mm·s^{-1} (1%) and 30.48 mm·s^{-1} (2%) were omitted. Also, the higher cutting speeds, for a material thickness of 5 mm, were not used for the same reason as for the 1.5 "(38.1 mm) lens, see Table 1.

Cutting speed in the presence of a lens with a focal length of 4 "(127.0 mm) caused cutting through for a material thickness of 5 mm at a minimum feed rate of 15.24 mm·s^{-1} (1%), see Table 1. There was a large melting of the surfaces created by the cuts. This melting of the material causes a very wide cutting groove with rounded edges.

Table 1. Working conditions testing.

Testing sample			1	2	3	4	5	6
P	(% / W)		100 /100					
f	(" / mm)		1.5 / 38.1		2.5 / 63,5		4 / 127.0	
t	(mm)		3	5	3	5	3	5
v_f	(% / mm·s^{-1})	1 / 15.24	Yes	Yes	-	Yes	Yes	Yes
		2 / 30.48	Yes	Yes	-	Yes	Yes	No
		3 / 45.72	Yes	Yes	Yes	Yes	No	No
Through		5 / 76.20	Yes	No	Yes	-	-	No
Yes/No		7 / 106.68	Yes	No	Yes	-	-	No

2.2 Preparation of samples for measurement width of the cut

To produce samples intended for measurement, identical board from PMMA were used, as in determining the optimal cutting speeds, and lenses with focal lengths of 1.5 "(38.1 mm) and 2.5 " (63.5 mm) see Table 2. Five samples were produced for the selected cutting conditions.

A comparison of the cutting width would not have been possible, so a lens with focal of 4 " (127.0 mm) was excluded from the production of groove width measurement samples.

Table 2. Production of samples for cutting width measurement.

Group sample		1	2	3	4
P	(% / W)	100 /100			
f	(" / mm)	1.5 / 38.1	1.5 / 38.1	2.5 / 63.5	2.5 / 63.5
t	(mm)	3	5	3	5
v_f	(% / mm·s^{-1})	3 / 45.72			

3. Width cut measurement

The measurement was made using a Carl Zeiss workshop microscope (Figure 2) using a 10x magnification lens. This device allows measurements with an accuracy of 0.001 mm. the resolution 0.001 mm with a measuring range of 200 mm longitudinally and 100 mm transversely.

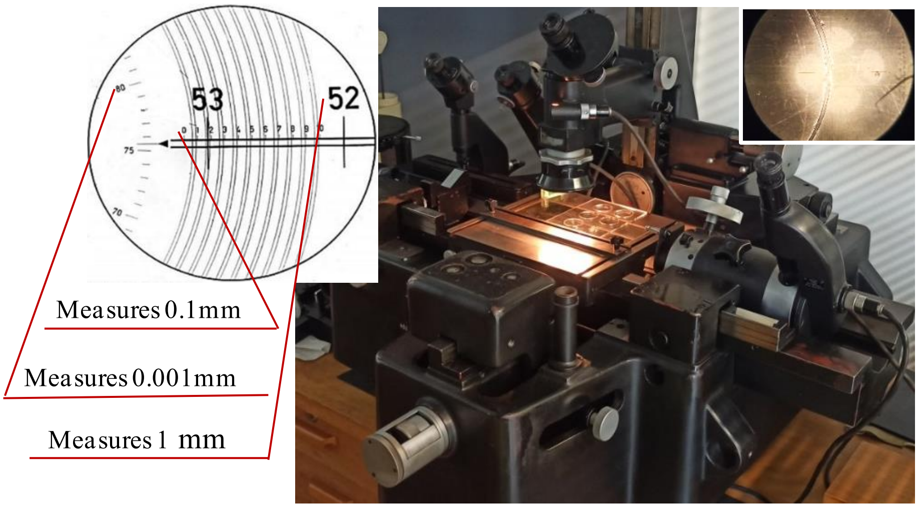

Figure 2. Measurement device.

The measurements were made on inner and outer circular samples made with lenses a focal length of 1.5" (38.1 mm), 2.5" (63.5 mm), on sheet board with a thickness of 3 mm and 5 mm with a power of 100 W and cutting speed of 45.72 mm·s^{-1}. Cutting a circular trajectory into the material allowed the measurement of the diameter on a circular sample separated from the blank and measurement of the inner diameter of the resulting hole in the plate. All diameters were measured on the upper and lower surfaces of the machined material, in vertical and horizontal directions.

The measured dimension is indicated by symbols in the tables and graphs: d_{TV} (outer dimeter on the top surface in the vertical direction), d_{BV} (outer dimeter on the bottom surface in the vertical direction), d_{TH} (outer dimeter on the top surface in the horizontal direction), d_{BH} (outer dimeter on the bottom surface in the horizontal direction), D_{TV} (inner diameter on the top surface in the vertical direction), D_{BV} (inner diameter on the bottom surface in the vertical direction), D_{TH} (inner diameter on the top surface in the horizontal direction), D_{BH} (inner diameter on the bottom surface in the horizontal direction), Table 3, Figure 3.

In the Table 3 is shows a case, as an illuminating example, for a lens with a focal length of 1.5" (38.1 mm) and a material with a thickness of 3 mm with the measured end coordinates of the samples x_1, x_2. This is the average value $\bar{x}$ for the vertical diameters d_{TV} and d_{BV}. In this way it was processed all measured data from which individual evaluations are based.

Table 3. Summary of results of outer top and bottom diameter

Sample	x_1	x_2	d_{TV}	x_1	x_2	d_{BV}
-			(mm)			
1	123.243	152.008	28.765	123.056	152.207	29.151
2	98.898	127.669	28.771	98.684	127.854	29.170
3	83.379	112.199	28.820	83.146	112.351	29.205
4	58.784	87.593	28.809	58.612	87.799	29.187
5	87.393	116.211	28.818	87.129	116.299	29.170
$\bar{x}$			28.797			29.177

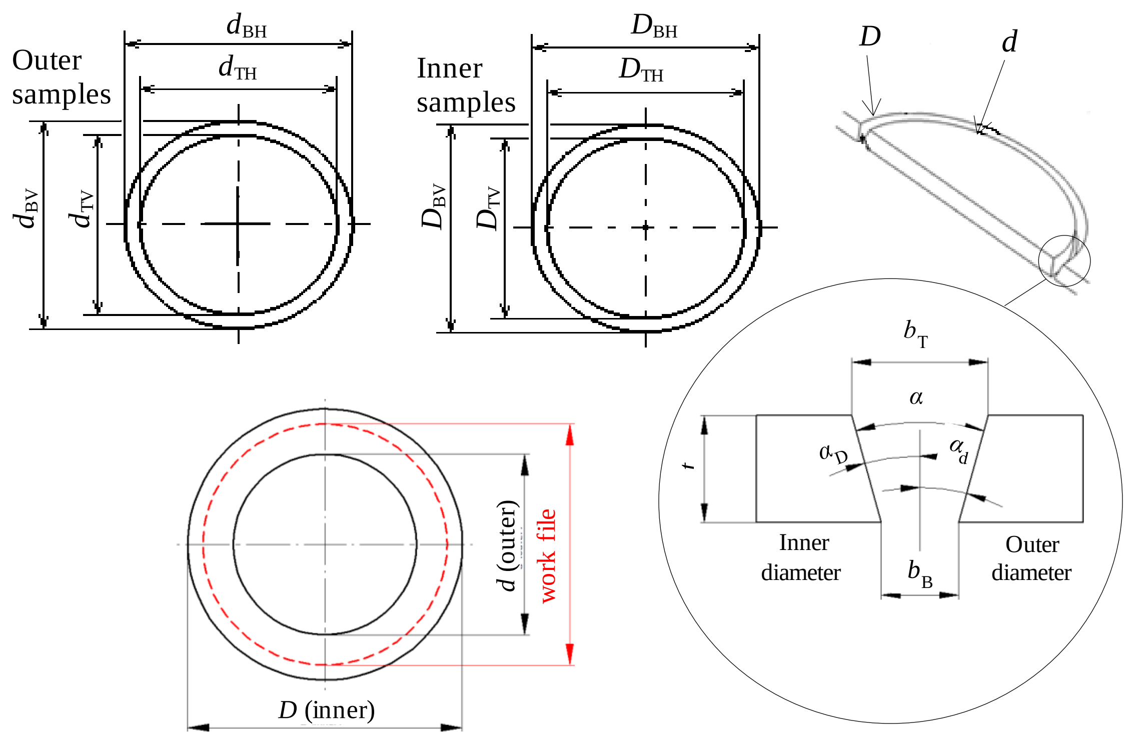

Figure 3. Comparison depth of cutting speed for engraving.

The measured values of the diameters of the outer and inner dimensions are shown in Table 4. There is a noticeable effect of the thickness of the blank and the focal length on the dimensions of the measured diameters. At a focal length of 2.5 " (63.5 mm), the outer diameter decreased, and the inward diameter increased. The evolution of a wider cutting groove with a larger focal length can already be presumed.

4. Results

The subject of the assessment are the diameters of the individual samples, the width of the grooves and the chamfering created by the laser beam and how the measured dimensions differ from the graphic file.

In all cases, smaller dimensions were achieved for outside diameters and circle dimensions for inside diameters were larger than the dimension defined by the machining file.

4.1 Diameter samples

In the vertical direction, dimensions were measured that differed significantly between the lenses used. The distinctly noticeable difference in measured dimensions prevails in the sheet thickness of 5 mm, see Table 4 (As an example, it is shown here only for the outer diameters).

This is mainly to the smaller loss of material by evaporation when using the 1.5" (38.1 mm) focal length distance. In the horizontal direction of measurement, the differences were smaller than in the thickness 3 mm.

Table 4. Diameters for different sheet thicknesses and different focal lengths.

f	(″/ mm)	1.5 / 38.1	2.5 / 63.5	Δ (mm)	1.5 / 38.1	2.5 / 63.5	Δ (mm)
t		3			5		
d_{TV}	(mm)	28.797	28.481	0.316	29.209	28.599	**0.610**
d_{BV}		29.177	28.886	0.291	29.589	29.044	0.545
d_{TH}		29.167	28.897	0.270	29.189	28.964	0.225
d_{BH}		29.542	29.306	0.236	29.580	29.435	0.145
D_{TV}		30.343	30.718	**0.375**	30.687	30.513	0.174
D_{BV}		30.012	30.330	0.318	30.294	30.061	0.233
D_{TH}		30.729	30.915	0.186	30.575	30.866	0.291
D_{BH}		30.376	30.527	0.151	30.191	30.390	0.199

Δ Difference of diameters with for focal lengths

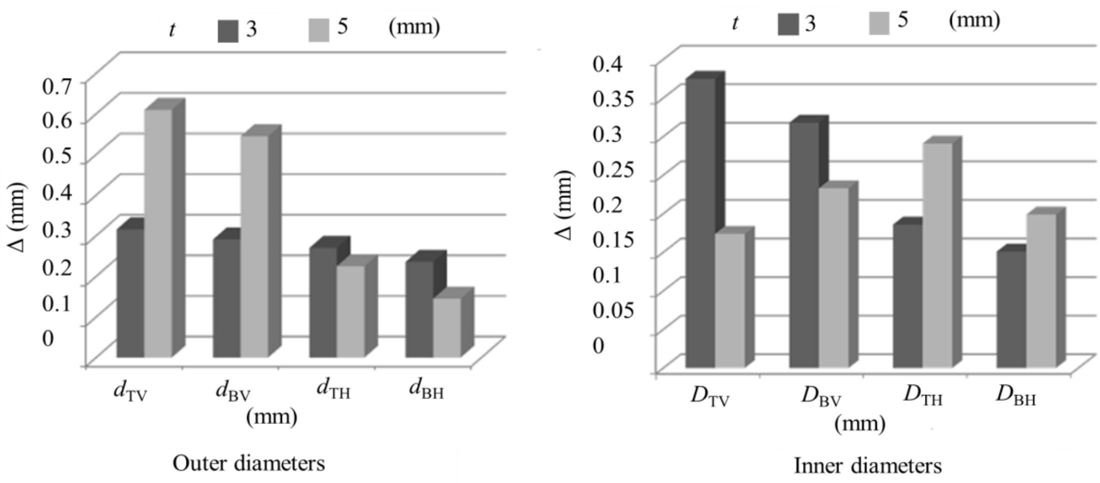

Figure 4. Comparison diameters.

The parameters of the internal dimensions of the samples did not reach such differences as in the previous case. The largest achieved values of diameters were with a focal length of 2.5" (63.5 mm) on the top surface in the horizontal direction. On the inner diameters, the differences are not so noticeable, since the change in focal length did not cause much change in the loss of material by evaporation, as with the outer dimensions.

In the vertical direction of measurement, larger values of differences prevailed on the sheet thickness of 3 mm. However, the results in most cases are not much different from the outer diameters. The differences are caused by the orientation of the larger part of the groove into the outer diameter of the sample.

4.2 Cutting width

The creation of different values of the cutting groove width on the top surface of the machined sheet laser beam input, and the bottom surface, laser beam output, of the semi-finished product was presumed already during the production of samples, the cross-section of the material will differ after its thickness.

The location and orientation of the grooves is defined by the designation of the width of the cut: b_{TV} is cutting width measured vertically on the top surface, b_{BV} is cutting width measured vertically on the bottom surface, b_{TH} is cutting width measured horizontally on the top surface, b_{BH} is cutting width measured horizontally on the bottom surface. The measured cutting widths are mentioned in Table 5.

Table 5. Cutting width for focal length and material thickness

f	(" / mm)	1.5 / 38.1		2.5 / 63.5	
t		3	5	3	5
b_{TV}	(mm)	0.773	0.739	1.119	0.957
b_{BV}		0.418	0.353	0.722	0.509
b_{TH}		0.781	0.693	1.009	0.950
b_{BH}		0.417	0.306	0.611	0.478
b_{TV} - b_{BV}		0.356	0.387	0.397	0.449
b_{TH} - b_{BH}		0.364	0.388	0.399	0.473

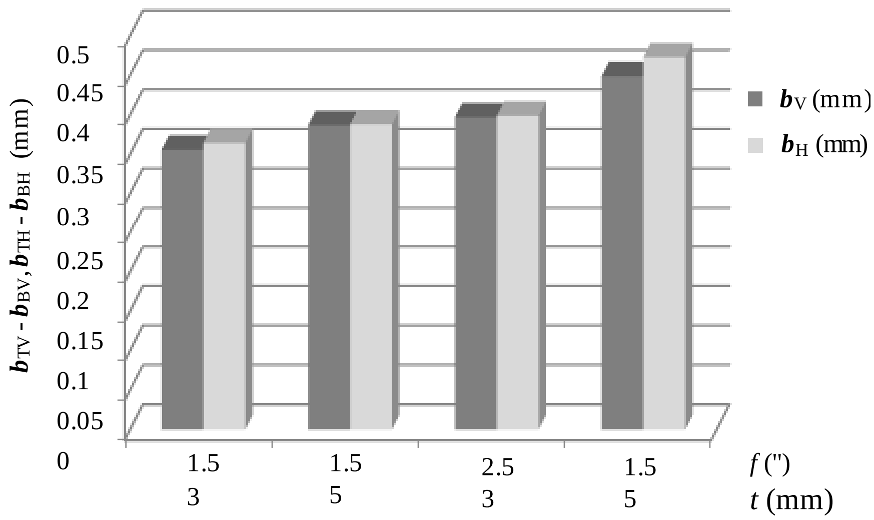

Figure 5. Dependence of widths on focal length and material thickens.

The measured values show that the groove formed is in all cases wider on the surface of the material than on its bottom. For a cut with a focal length of 2.5 " (63.5 mm), the groove widths were significantly greater for both material thicknesses than at a focal length of 1.5" (38.1 mm), which is caused to the concentration of the laser beam over a larger area with increasing focal length.

The values of the difference in the width of the groove on the surface where it is widest and from the bottom-side of the material where it is narrowest do not change much in individual directions therefore, the vertical or horizontal cutting trajectory does not affect the difference between top and bottom values dimension. The largest difference was achieved in a blank with a thickness of 5 mm and a focal length of 2.5 " (63.5 mm). This is a difference in the order of hundredths of a millimetre which may be caused to the material and the focal lens used. In this case, there was a greater melting of the resulting edges, thus also inaccuracies at the edge of the sample. According to the results, it can be concluded that the size of the focal length influences the width of the cut. With increasing focal length, the width of the groove on both the surface and the lower surface also increases.

The horizontal direction shows a greater difference in width on the bottom surface and on the top surface. The difference is very small and could have been caused by manufacturing inaccuracies. A slight increase is, both with a change in thickness and with an increase in the focal length of the lens. It follows that when using a material with a greater thickness and greater focal length distance of the lens, the value of the upper and lower width of the given groove should increase.

The size of the grooves is not symmetrically distributed on the trajectory of the cut. This geometry was defined by the graphics software as 30 mm. The Table 6 shows the width of the groove into the inner and outer sample. The interface for the width distribution is therefore the set geometry of the sample, respectively the expected path of the laser beam. The values for the outer diameter *d* are such that the dimension extends into the inner side of the circular contour. Conversely, the part of the groove extending beyond the circle with a diameter of 30 mm falls on the inner diameter *D*.

Table 6. Areas of the width of the cut for diameter 30 mm.

f	(" / mm)	1.5 / 38.1		2.5 / 63.5	
t		3	5	3	5
d_{TV}	(mm)	–0.602	–0.396	–0.759	–0.701
d_{BV}		–0.412	–0.206	–0.557	–0.478
d_{TH}		–0.416	–0.406	–0.552	–0.517
d_{BH}		–0.229	–0.210	–0.347	–0.283
D_{TV}		+0.172	+0.344	+0.359	+0.257
D_{BV}		+0.006	+0.147	+0.165	+0.031
D_{TH}		+0.365	+0.288	+0.458	+0.433
D_{BH}		+0.188	+0.095	+0.264	+0.195

The distribution of the width of the cutting joint is also given in percentage. Each width of dimension *b* is expressed according to its position relative to the defined diameter of 30 mm as a percentage fraction. The measured data show that all cutting widths extend mostly into the inner part of the circle (outer diameter of the sample). The largest loss, relative to the width at the outer diameter, was observed for the lens with a focal length of 1.5" (38.1 mm), a material thickness of 3 mm and a vertical orientation when measured on the underside of the sample. This high value may be due to the greater intensity of the beam at a given point and the smaller thickness of the material. On the top surface of the defined circle, the beam entered and also exited the section. From a point on the vertical axis of the circle, the beam moved clockwise along the circle.

Table 7. Areas of the width of the cut for diameter 30 mm.

f	(" / mm)	1.5 / 38.1		2.5 / 63.5	
t	(mm)	3	5	3	5
b_{TV}	(mm) (%)	0.366	0.369	0.559	0.478
d_{TV} / D_{TV}		77.8 / 22.2	53.5 / 46.5	67.9 / 32.1	73.2 / 26.8
b_{BV}		0.209	0.176	0,361	0.254
d_{BV} / D_{BV}		**98.6 / 1.4**	58.3 / 41.7	77.1 / 22.9	93.9 / 6.1
b_{TH}		0.390	0.346	0,504	0,475
d_{TH} / D_{TH}		53.3 / 46.7	58.5 / 41.5	54.7 / 45.3	54.4 / 45.6
b_{BH}		0.208	0.153	0.305	0.239
d_{BH} / D_{BH}		54.9 / 45.1	68.8 / 31.2	56.8/43.2	59.2 / 40.8

The achieved cutting widths relative to the defined path of the laser beam (dashed circle) can be seen in Figure 3, 6. The displacement from the designed trajectory expresses how the formed groove extends into the outer diameter *d* and the inner diameter *D*. Made cuts trajectory deviate significantly from the designed centre. Positive values indicate an increase in the inner diameter and negative values indicate an increase in the outer diameter. Part of the width of the cut *b* in the vertical direction extends more into the outer diameter. In the horizontal direction, there is a more uniform distribution of the width of the groove created by the evaporation of the material.

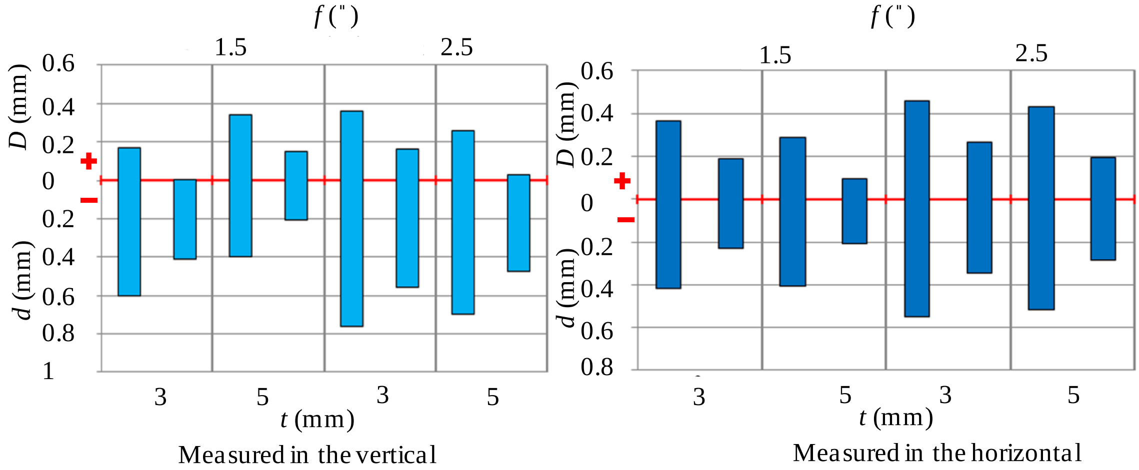

Figure 6. Groove width spread with material thickness.

4.3 Cutting chamfer

In the vertical direction, the largest angle of inclination was achieved for a material thickness of 3 mm. For this material, the angles of α_{DV} (Table 8, Figure 3, 7) are considerably larger in the case of the inner diameter and the angles of α_{dV} of the outer diameter. This corresponds to the total angle α_V, which is formed by the cutting groove. A larger angle of chamfer on thinner material is caused to greater edge melting.

Table 8. Areas of the width of the cut for diameter 30 mm.

f	(" / mm)	1.5 / 38.1		2.5 / 63.5	
t	(mm)	3	5	3	5
α_{dV}		3.631	2.178	3.876	2.548
α_{DV}		3.159	2.255	3.708	2.590
α_V	(°)	6.790	4.433	7.584	5.138
α_{dH}		3.593	2.241	3.911	2.700
α_{DH}		3.275	2.203	3.700	2.726
α_H		6.868	4.559	7.611	5.426

In the horizontal direction, the data are very similar to the vertical direction of measurement. The largest chamfer angle α_{DH} was shown on the inner sample and also the chamfer angle α_{dH} on the outer sample of the 3 mm thick material. This may be caused to the easy penetration of the beam through the material and from them reason melting of the cutting surfaces.

The bevel angle of the 5-mm-thick sheet differed not much for both focal lengths used.

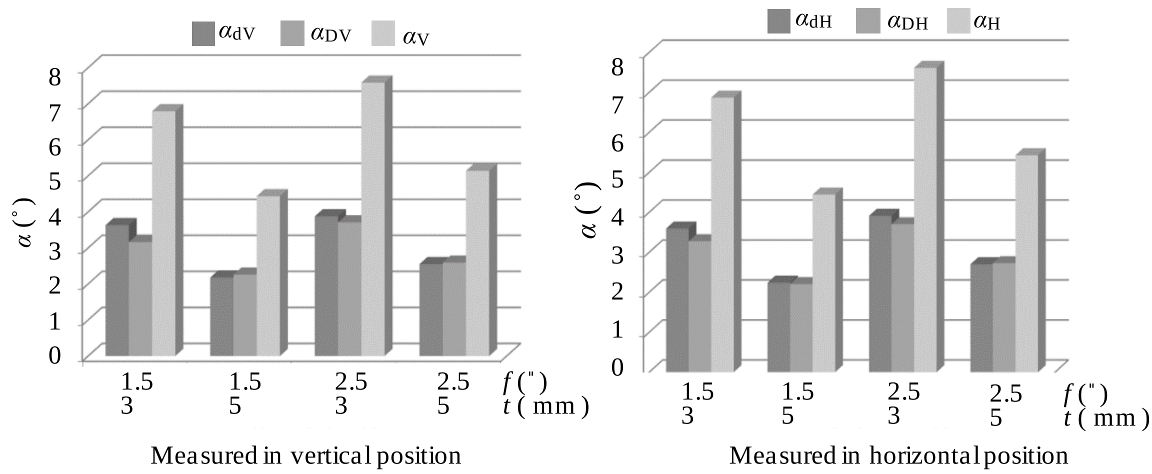

Figure 7. Groove width spread with cutting angle.

5. Conclusion

The aim of the study was to find out how the dimension of the final product will differ from the dimension defined by the machining file.

The groove created by the cut was in all cases more width on the surface of the blank than on the underside. This means that on the outer and inner sample, the angle of chamfer of the surfaces created by the cut was created, which differed significantly especially when the thickness of the material changed, where a larger chamfer angle was achieved in a semi-finished product with a thickness of 3 mm.

All section widths were oriented with the larger part towards the centre of the defined circle. Larger cutting widths were achieved by using a lens with a focal length of 2.5" (63.5 mm), where the beam was focused on a larger area of the material. To achieve more accurate dimensions on the product, it would be more appropriate to use a focal length of 1.5 " (38.1 mm), where there was a smaller width of the groove and also less bevel between the top and bottom surface of the sheet.

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