JPMTR 114 | 1815
DOI 10.14622/JPMTR-1815
UDC 535.4-023:772.2

Research paper
Received: 2018-07-16
Accepted: 2018-12-21

Improvement of the optical system in direct laser engraving to increase the resolution of printing plates

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Abstract

At the present time the direct laser engraving (DLE) technology is the most economical and ecological one to produce flexographic printing plates. But small resolution caused by lasers with a wavelength of 10.6 µm led to insufficient quality of final print production. Thus an actual problem is the resolution increasing of DLE process, which will lead to increased quality of prints. The aim of this paper is to present the method of resolution increasing of direct engraving equipment. The calculation and design of an optical telescope intended to increase the resolution of the laser apparatus has been carried out. Testing of the performance of the telescopic system has been performed by calculating the distribution of the intensity of radiation in the focus of the optical system of the apparatus with and without a telescope with the help of a specialized application for optical designing, ZEMAX. A range of drawings and the simulation of a 3D model of the telescope have been done in the SolidWorks design application based on the conducted calculations of the optical system. The telescope then has been made and incorporated into the laser-optical system of the laser engraving device. The quality of focusing of the optical system before and after the modernization has been studied by engraving on a thermo sensitive film of a specially created test-scale that allows determining the convex caustic shape of the beam after its focusing by the optical system. During the comparative analysis of the laser engraving device before and after the optical system upgrade using a test image, it has been found that its technical parameters with respect to the resolution have been doubled.

Keywords: flexographic printing form, focusing spot, telescopic system, halftone resolution

1. Introduction and background

Historically, direct engraving of flexographic printing plates has begun the use of lasers in printing industry. This technology has long been widely used in flexographic printing enterprises for rubber printing plates manufacturing (Nykyrui, 2009). In this case, the equipment that works according to this method allows the engraving of closed images, that is, to form an infinite pattern (Bukwaits, 2006; Vefers and Apps, 2006). The essence of the technology of direct laser engraving (DLE) is the formation of printing elements by direct processing of the original material (rubber or special polymers) by a laser beam, with the ready-to-use plate obtained immediately after the laser treatment (Graßler, 2011).

The vast majority of manufacturers of DLE devices are using CO_2 lasers with an approximate radiation wavelength λ = 10.6 µm, giving up high resolution in favor of processing a wide range of materials. The essential disadvantage of CO_2 lasers is that they do not allow the recording of image with the screen ruling required for the current quality level of flexo printing, such as 180 lpi. However, this does not mean that the method of direct engraving is not suitable for high-quality flexographic printing. By choosing a laser with a shorter wavelength, it is possible to provide the necessary conditions for high-resolution laser engraving, and therefore, to realize the production of high screen ruling of flexographic plates. The most suitable for this purpose is to choose a near infrared (NIR) laser whose wavelength of radiation is λ = 1.064 µm. Under other equal conditions in a system with such a laser, it would be possible to obtain a spot of focused laser radiation ten times smaller than that of a CO_2 laser. Choosing a computer-to-plate (CtP) device designed for laser ablation mask system (LAMS) technology will allow upgrade of the system to a smaller focusing spot by upgrading the optical unit. Obviously, the device is used as the basis, in the software-hardware part of which there is the ability to work with the resolution of 5 080 dpi. This will fulfil all modern requirements for the manufacturing process of flexographic plates. But because of the obvious prospect of using a fiber laser to manufacture flexographic plates, the introduction of this technology has been significantly hampered by a number of circumstances associated with materials for laser engraving that are sensitive to wavelengths of 1.06 μm. First, the spectrum of materials here is substantially fewer than for a CO_2 laser. Secondly, materials suitable for the production of flexographic plates in terms of printing properties (ink resistance, hardness, circulation durability) were practically inaccessible for a long time. In addition, these materials were preferably less sensitive to the wavelengths of 1.06 μm than to 10.60 μm, which led to lower productivity and caused the need for high-power lasers (Laskin, et al., 2001).

In order to provide the features of direct engraving technology that are acceptable for today's printing quality level, it is necessary to have plate materials with sufficient sensitivity for the NIR range (in particular, the wavelength of 1.06 μm) and to meet other requirements of the printing process (ink resistance, circulation durability, hardness, etc.). Such materials for DLE can be: BöttcherFlex 787 BN (SBR); BöttcherFlex 732 BN (EPDM), plates for DLE of the companies ContiTech, Kodak, etc. (Böttcher systems, 2011; ContiTech, 2017; Kodak, 2013).

In order to successfully implement the DLE technology in the production process of flexo printing plates, a detailed study of the influence of the characteristics of optical focusing systems on the technological parameters of engraving is required. Since the effectiveness of most laser processing processes is largely determined by the concentration of energy in the focusing spot, the main attention in the design of focusing systems should be paid to ensuring the minimum size of the focusing spot.

However, in order to improve the technology of manufacturing flexo printing plates by DLE method, it is necessary to increase the resolution of laser equipment. In its turn, in order to increase the resolution, it is necessary to reduce the size of the processed pixel, by reducing the minimum amount of engraving. This can be achieved by reducing the focusing spot, that is, beam waist diameter.

2. Materials and methods

The LaserGraver equipment for the production of flexographic printing plates, which was equipped with a fiber laser with the radiation wavelength of 1.06 μm, was chosen to improve DLE technology. The parameters of the focusing system were calculated based on the following laws of optics. Obtaining the smallest focusing spots and the highest irradiation intensity is possible only in beams with a relatively simple configuration with the lowest order of transverse electromagnetic mode (TEM_{00}). The intensity distribution in the resonator mode of the lowest order TEM, I_{00} has a Gaussian form given by Equation [1]:

$$I_{00}(R) = \exp\left(-2R^2/w^2\right) \qquad [1]$$

where R is a radial coordinate and w is a radius of the beam cross section, on which the TEM_{00} mode intensity is $1/e^2$ times smaller than the intensity on the axis of the beam (Ready, 1971), e being the Euler's number i.e. the base of the natural logarithm. If such beam is focused on the optical axis in focus of the lens, then the diameter of the focus spot d_k is determined by Equation [2] (Grigoryants, Shyganov and Misurov, 2006):

$$d_k = d_W + d_a \qquad [2]$$

where the component d_W is conditioned by the divergence of the beam, and d_a is conditioned by aberrations (Equations [3] and [4]).

$$d_W = FW \qquad [3]$$

$$d_a = \delta q'/2 \qquad [4]$$

where F is a focusing distance, W (Equation [5]) is a divergence of the beam and $\delta q'$ is a transverse spherical aberration.

$$W = 1.22\,\varepsilon\lambda/D \qquad [5]$$

where ε is an empirical coefficient that takes into account the divergence increasing in the resonator (the value of this coefficient is determined by measuring the true divergence of the laser beam), λ is the wavelength of the radiation and D is the width of the laser beam that enters in the focusing lens. Consequently, the diameter of the focused spot that is due to the beam divergence can be determined by Equations [6] and [7]:

$$d_W = 1.22\,\varepsilon\lambda F/D \qquad [6]$$

$$\delta q' = \sum_{k=1}^{n} \frac{P_k (D/2)^3}{2F^2} \qquad [7]$$

where n is the number of optical surfaces, and P_k is the parameter, which is calculated according to Equation [8]:

$$P_k = (\Delta\alpha_k/\Delta\mu_k)^2 \Delta\alpha_k \mu_k \qquad [8]$$

where $\Delta\alpha_k = \alpha_{k+1} - \alpha_k$, α_k is a tangent of the angle of a peripheral laser beam after its refraction on the optical surface; $\Delta\mu_k = \mu_{k+1} - \mu_k$; $\mu_k = 1/n_k$ is a reciprocal of the refractive index.

The formula to determine a focus spot size, taking into account the beam divergence and aberrations, then can be written as Equation [9]:

$$d_k = \frac{1.22\varepsilon\lambda F}{D} + \frac{P^* D^3}{32F^2} \qquad [9]$$

where $P^* = \sum_{k=1}^{n} P_k$

We can increase the width of the laser beam by factor V by its passing through a telescope, which transfers the input parallel beam of rays with the cross section diameter D_1 into the output parallel beam with a bigger cross section diameter D_2.

$$V = \frac{F_1}{F_2} = \frac{D_1}{D_2} \qquad [10]$$

Radii of lens surface curvature and its focusing distance are related by the following ratio:

$$\frac{n_0}{F} = (n - n_0)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) + \frac{(n - n_0)^2}{n r_1 r_2} d_\ell \qquad [11]$$

where n is refraction index of the lens material, n_0 is refraction index of the medium surrounding, d_ℓ is the thickness of the lens (the distance between the spherical surfaces along the optical axis), r_1 is the curvature radius of the surface, which is closer to the light source (further from the focusing area, hereinafter the first surface), r_2 is the curvature radius of the surface, which is further from the light source (closer to the focusing area, hereinafter the second surface). In Equation [11], for the r_1 radius the sign is taken as plus if the surface is convex, and minus if concave. For r_2 on the contrary, we use plus if it is concave, and minus if it is convex. For a thin lens, when the distance between the vertices of the surfaces (the thickness of the lens) d_ℓ is much smaller than the radius of curvature of the surfaces r_1 and r_2, we accept the condition $d_\ell = 0$.

Using Equation [11] and appropriate mathematical operations, the ratio of radii of curvature r_1 and r_2 for the twin-curved and flat-convex lenses were determined. For a twin-curved lens, the ratio between r_1 and r_2 is (Equation [12]):

$$r_1 = -\frac{(n-1)r_2 + d_\ell \dfrac{(n-1)^2}{n}}{\dfrac{r_2}{F} + (n-1)} \qquad [12]$$

For a flat-convex lens, the ratio between r_1 and r_2 will look the same but with an opposite sign (Equation [13]):

$$r_1 = \frac{(n-1)r_2 + d_\ell \dfrac{(n-1)^2}{n}}{\dfrac{r_2}{F} + (n-1)} \qquad [13]$$

To test the performance of the telescopic system, the calculation of the radiation intensity distribution in the focus of the lens for basic and upgraded optical schemes was performed using a specialized ZEMAX optical design program (Zemax, LLC, USA).

The quality of focusing of the optical system before and after modernization was studied by engraving of test-scale No1 on a thermosensitive film. This test scale (Figure 1) consists of a 1-pixel line image (1 pixel = 10 μm at the imaging resolution of 2 540 dpi) and it allows determining the caustic shape of the beam waist after focusing it by the optical system. The test scale was engraved on a black mask layer of thermosensitive polyethylene terephthalate / poly l-lysine (PET/PLL) film at different values of the lens focus position relatively to the material surface (z_F).

Figure 1: Test scale No1 to determine the shape of beam waist

The images of the test scale No1 received on the PET/PLL film were analyzed with the help of Flexometer software-hardware complex equipped with an optical microscope and the width of lines s was measured.

The optical system of LaserGraver equipment shown in Figure 2, selected for the modernization, consists of ytterbium fiber laser, modulator, optical trap, lens, and beam focusing mechanism. The laser beam focuses on the printing form, using the tele-centric lens and beam focusing mechanism. For convenience, we will call this optical system as "basic".

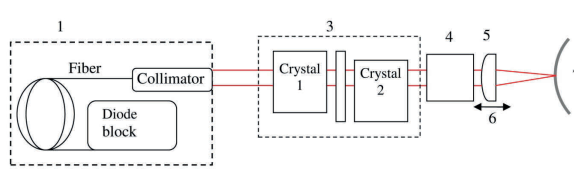


Figure 2: Schematic diagram of the basic optical system: (1) laser, (3) modulator, (4) optical trap, (5) lens, (6) movement mechanism, (7) printing form

3. Improvement of engraving system

Taking into account that the design parameters of the laser resonator and the laser collimator are determined by the equipment manufacturer, their initial characteristics are unaltered. Obviously, there are two ways to reduce the focusing spot – decrease the focusing distance of the lens and increase the input aperture of the beam (see Equation [10]). It is not advisable to reduce the focusing distance of the lens as it causes the structural changes of the focusing system, the system of output of combustion products, etc. Therefore, it is optimal to increase the input aperture of the laser beam by installing a telescope that will provide a small diameter of the focusing spot, and hence the higher resolution of the system. Since the input and output beams of the telescope are parallel, it is possible to place the telescope between the collimator and the modulator, the distance between which will determine the maximum overall dimensions of the telescope.

LaserGraver resolution is 2 540 dpi. To achieve the value of 5 080 dpi, the size of the pixel should be twice smaller during engraving. This can be achieved by halving the diameter of the beam in the focusing area. Consequently, according to Equation [6], it is necessary to double the diameter of the cross section beam in the lens, using the telescopic system with magnification $V = 2$ according to Equation [10].

It should be noted that increasing of beam aperture results in decreasing of the length of the longitudinal spherical aberration ΔF and, accordingly, in decreasing of the constriction length (see Equation [7]), so the depth of engraving is reduced.

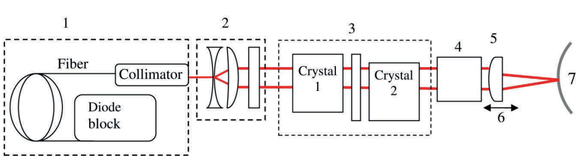


Figure 3: Schematic diagram of modernized optical system: (1) laser, (2) telescope with compensator, (3) modulator, (4) optical trap, (5) lens, (6) movement mechanism, (7) printing form

Figure 3 shows a schematic diagram of the optical system, which, unlike the basic optical system, includes telescope with compensator. For convenience, we will call this optical system as "modernized". As the telescope is located between the laser and the modulator, its maximum length is 30 mm.

The magnification of the telescopic system should be 2. Taking into account the tolerances on the body, we set the distance between the lenses of the telescope at about 18 mm. In this case, the focusing distance of the lenses should be as large as possible in order to reduce the effect of the transverse spherical aberration (see Equation [7]). It is possible to fulfill this condition by using, instead of twin-convex lenses, a biconcave and flat-convex lens, whose focuses will be approximately 17.5 mm and 35.0 mm, respectively. In addition, twin-convex (cumulative) lenses create a spherical aberration $\delta S < 0$ for all areas. In contrast, the biconcave (dispersive) lenses have a spherical aberration of the opposite sign, $\delta S > 0$. The flat-convex lenses have very small aberrations. Combining such lenses, it is possible to significantly reduce the spherical aberration of the telescope.

From the limitation of the maximum thickness and height of the collimator, we will determine the maximum diameter of the lens D_{max}, which, taking into account the tolerances on the body, will be D_{max} = 15 mm. Taking into account Equations [7] and [8], it is not feasible to reduce the diameter without the need. Since the elements of LaserGraver laser system are made from quartz, to manufacture the lenses of the telescope, we also used quartz, whose refraction index is $n = 1.4584$. In addition, quartz glass is characterized by high thermal resistance, which is essential for working with laser radiation.

The basic scheme of the telescope and the calculation of the beams are shown in Figure 4. The laser beam, whose cross section diameter is D_1, falls on the Lens 1, whose focusing distance is F_1. Refracted by the Lens 1, the beam falls onto the Lens 2, which forms a beam with the cross section diameter D_2. The Lens 1 is a twin-curved lens with first surface radius r_1 and second surface radius r_2. The Lens 2 is a flat-convex lens with first surface radius r'_1 and second surface radius r'_2. The focuses of the Lenses 1 and 2 are aligned at point A.

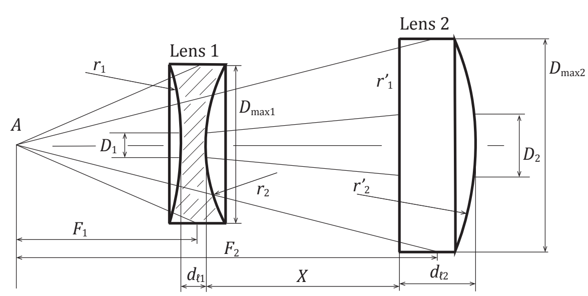
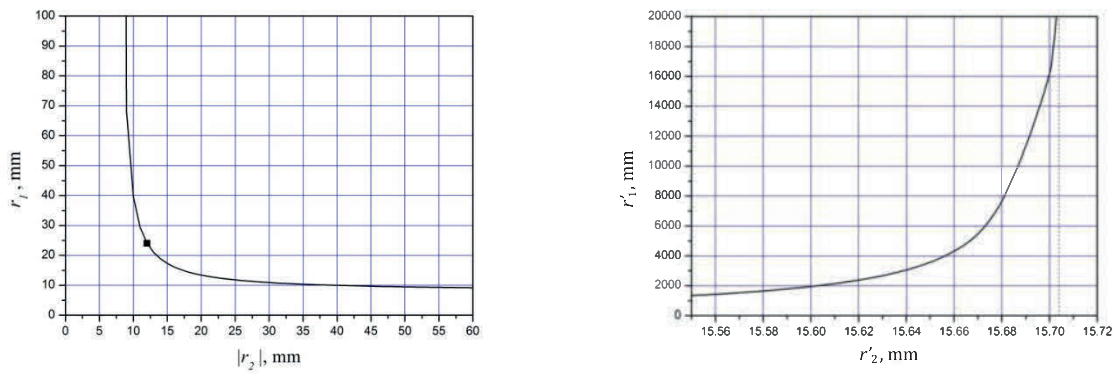


Figure 4: Schematic diagram of the telescope

Since the telescope operates in an air environment, the refraction index is $n_0 = 1$. The refraction index of quartz glass for the wavelength $\lambda = 1.064$ µm is $n = 1.450$. Using the Equation [11], by means of appropriate mathematical operations, the ratio of the radii of curvatures r_1 and r_2 for the twin-curved and r'_1 and r'_2 flat-convex lens (Equations [12] and [13], respectively) has been calculated, the results of which are presented in the graphs in Figure 5.

When calculating for the twin-curved lens, the value of the focusing distance is given as $F_1 = -17.54$ mm, and the value of the thickness of the lens $d_{\ell 1} = 1.8$ mm. The thickness of the lens should not be set too thin, since during polishing the lens is deformed, which makes it



a) b)

Figure 5: Ratio of the radii of the surface curvature for the twin-curved (a) and the flat-convex (b) lens

impossible to obtain precise surfaces and centering. For a twin-curved lens, the minimum permissible value of d_{l1} is determined by the ratio between the diameter and 1.5 $D_{max\,1}$.

An increase in the thickness of the lens leads to decrease in the intensity of the beam as a result of the weakening of the light flux in the environment. In Figure 5a the values of the surface curvature radii specified for manufacturing the twin-curved lens are denoted by the dot.

When calculating a flat-convex lens, the value of the focusing distance is given as F_2 = 34.92 mm, and the value of the thickness of the lens $d_{\ell 2}$ = 5.2 mm. According to the calculations, a graph of the dependence $r'_1(r'_2)$ has been constructed (see Figure 5b). The value of r'_2 goes to infinity. Under these conditions, the first surface of Lens 2 can be considered as a plane, and the radius of curvature of the second surface is r'_2 = 15.70 mm.

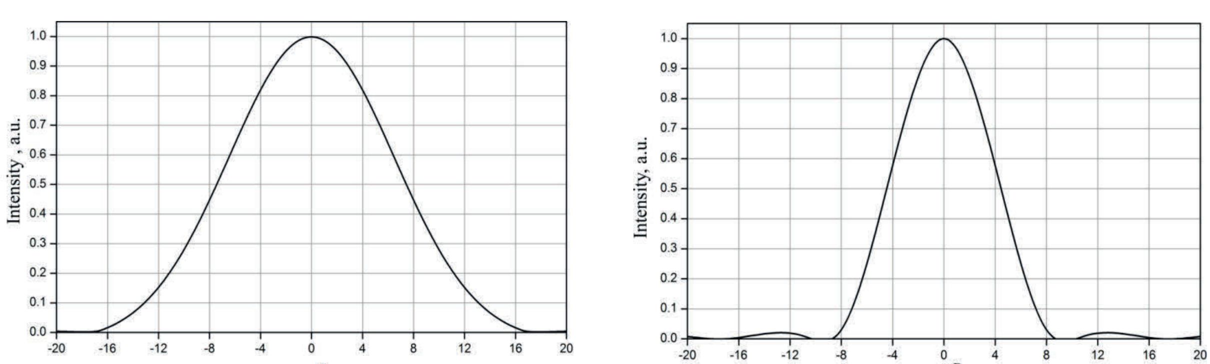
Thus, based on the conducted calculations of the surface curvature, an optical calculation of the beam passing through the telescope has been done, the data of which are presented in Table 1.

Table 1: Parameters of the telescopic system

Parameter	Lens 1	Lens 2
Lens focus	F_1 = –17.54 mm	F_2 = 34.92 mm
First surface radius	r_1 = 24.32 mm	r'_1 = 22141.35 mm
Second surface radius	r_2 = 11.94 mm	r'_2 = 15.70 mm
Lens thickness	$d_{\ell 1}$ = 1.8 mm	$d_{\ell 2}$ = 5.2 mm
Focal segment S_E	18.34 mm	–31.34 mm
Focal segment $S'_{E'}$	–17.94 mm	34.92 mm
Maximum diameter	11.0 mm	15.0 mm

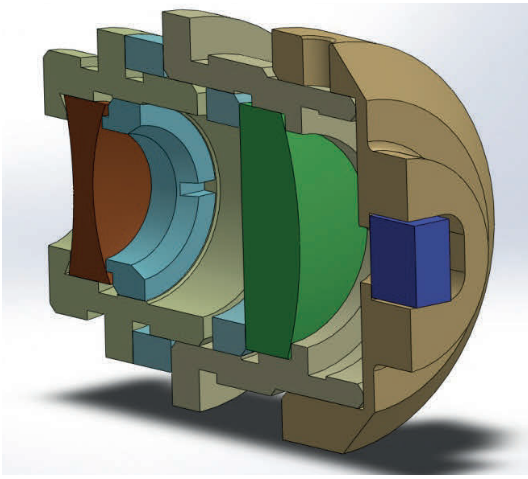
Verification of the telescope performance was carried out by calculation of the radiation intensity distribution in the focus of the lens for basic and modernized optical systems, using ZEMAX specialized program for optical designing (Figure 6). As it can be seen from Figure 6, the intensity distribution in the focusing area corresponds to Gauss's law. The focusing spot radius (R), defined by level $1/e^2$, for a basic optical system is about 12.5 µm (Figure 6a), and for the modernized system it is about 6 µm (Figure 6b). Consequently, the suggested telescope corresponds to its functional purpose.

According to the calculations, the drawing of the telescope details has been done using SolidWorks design program. The 3D model of the telescope, which consists

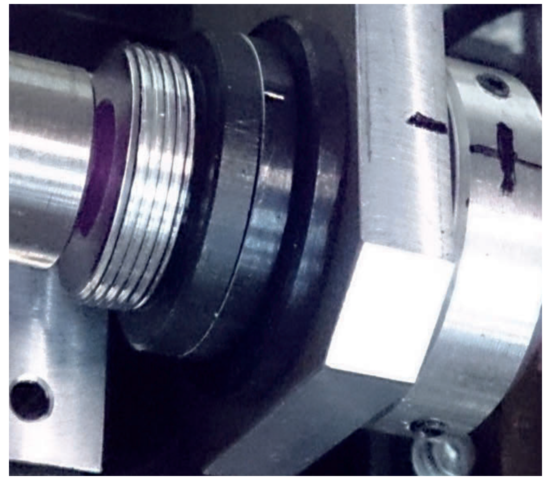


a) b)

Figure 6: The radiation intensity distribution in the lens focus for basic (a) and modernized (b) optical system



a)



b)

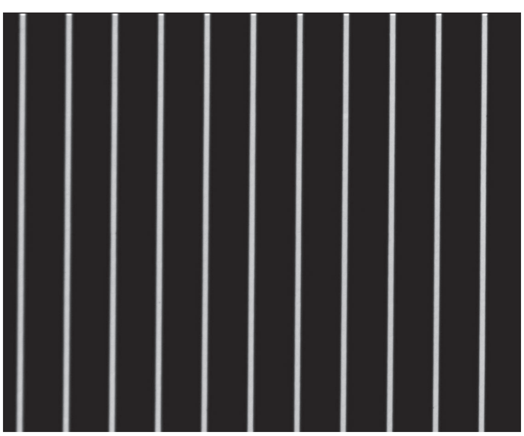
Figure 7: Section of a 3D model (a), and a photo of the telescope installed into LaserGraver optical system (b)

of body parts and two lenses, is shown in Figure 7a. The details were manufactured and the assemblage and alignment of the telescope was completed according to the drawings. Figure 7b shows a photo of the finished telescope.

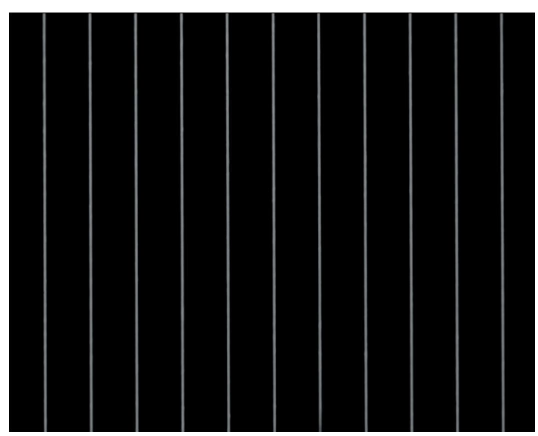
The telescope was installed into the optical system of LaserGraver equipment in accordance with the schematic diagram of modernized optical system shown in Figure 3. The modernized optical system of the equipment was tested to verify the deviation from the previous parameters and to check the correctness of the telescope position. After the test completing, control records have been made on a thermosensitive film.

4. Results and discussion

To experimentally determine the parameters of the beam waist in the focus of the lens, the test scale No1 (Figure 1) was engraved on the thermosensitive film at different values of the lens focus position relative to



a)



b)

Figure 8: Photos of test scale No1, engraved on the film using basic (a) and modernized (b) optical system

Table 2: Results of the test scale analysis obtained by Flexometer

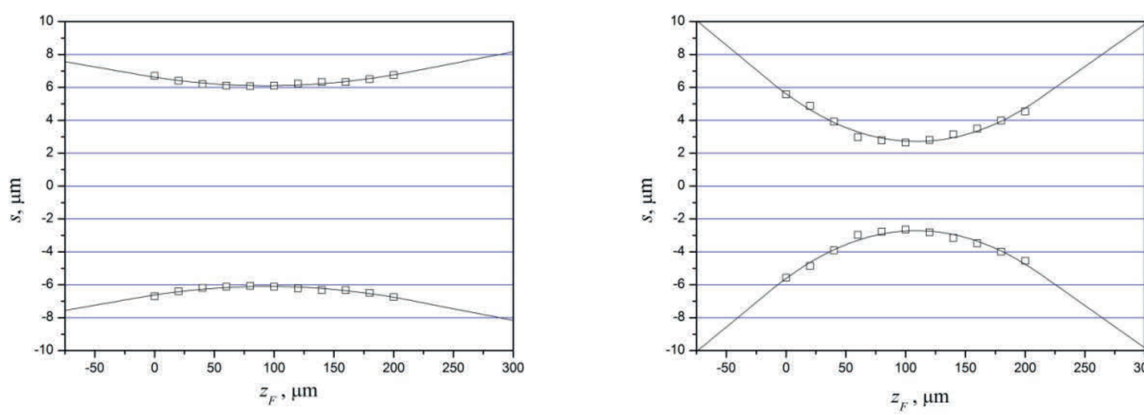
Parameter	Basic optical system	Modernized optical system
Number of analyzed lines	11	11
Average width of the line	12.57 µm	6.32 µm
Average squared deviation of line width	0.15 µm	0.17 µm
Minimal width of the line, s_{min}	12.45 µm	5.95 µm
Maximal width of the line, s_{max}	12.80 µm	7.18 µm

the film surface (z_F). The test scale was engraved using both (basic and modernized) optical systems. The laser radiation power during the test image engraving was about 15 W. The photos of the engraved tests are presented in Figure 8. Each of engraved lines was analyzed using Flexometer application and the results are presented in Table 2. As can be seen, the average width *s* of the line in the focus of the basic optical system is 12.57 μm, whereas of the modernized optical system the width is 6.32 μm. So, the lines are twice as narrow for the case of a modernized optical system.

Figure 9 presents schematic laser beam waist (caustic surface of the laser beam) for basic and modernized optical systems constructed on the basis of dependencies $s(z_F)$ (Nykyrui and Maik, 2016a).

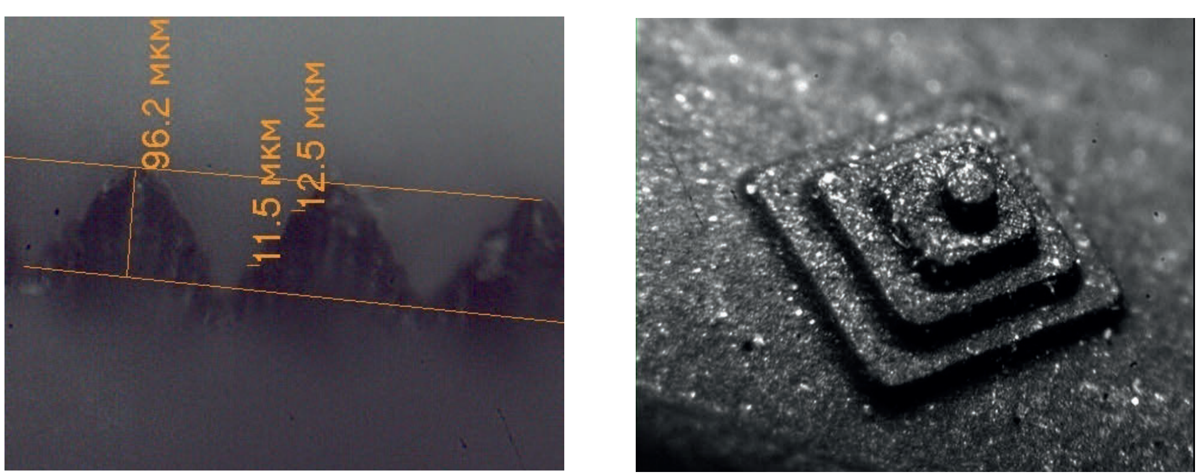
According to the results of the testing, the hardware parameters for the material being engraved for test were determined. The modernization of the optical system of the laser engraving device allowed reducing the discrete volume that is removed during DLE process. By changing parameters such as the beam power, the number of passes forming the profile, the lens focus position for each passage and the drum rotation speed of each passage gave us the opportunity:

- to develop the technology for the modification of geometric profile of printing elements on the printing plate made from DLE (Figure 10) and to conduct the studies on the influence of the geometric shape of the profile on the reproduction process and print characteristics (modification of the shape of small print element and single print element, modification of the deformation of print plates under pressure, and study of optical dot gain, elastic properties of print elements, etc.) (Nykyrui and Maik, 2012);



a) b)

Figure 9: Caustic surface of the laser beam for basic (a) and the modernized (b) optical systems



a) b)

Figure 10: Micro-photo of printing elements with modified profile in the shape of a pyramid with the step of 10 μm (note: MKM in picture stands for μm) (a), and single print element in the shape of a pyramid (dot width = 20 μm) with the step of 25 μm (b)

- to develop the technology of micro-screening of printing elements on the DLE materials and design different types of micro-screens, which allows to find the optimal type of micro-screen suitable for different types of inks and printing substrates that allows increasing of optical density of the imprints (Nykyrui and Maik, 2016b);
- to develop the technology for the production of flexographic printing plates with the height of printing elements below the level of the printing nip, which avoids excessive tone value increase of small dots of design with reduced pressure on the plate to print different tone values more evenly (Nykyruy and Mayik, 2017).

5. Conclusions

The method of increasing the resolution of the laser engraving equipment by modernizing its optical system was described. The calculation and the design of an optical telescope for reducing the laser spot size in the focus of the optical system were carried out. The telescope was produced according to the drawings and incorporated into the optical system of the laser engraving equipment. The increase in the resolution of the equipment was confirmed by the results of testing. Increasing the resolution of the laser engraving equipment allows not only improvement of the quality of material engraving, but also an opportunity for improvement of the flexographic printing plates by engraving.

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