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DETERMINATION OF THE CRITICAL VALUES OF POWER DENSITY IN LASER MARKING OF TEXTILE MATERIALS

Purpose. *Defining the applicability limits of the laser marking of cotton and polyester fabrics with two types of lasers:* L_1 *–* CO_2 *&* L_2 *– CuBr.*

Methodology. *Digital data obtained from an experimental study were systematized and processed analytically, and the results were presented graphically. The dependencies between the physical variables and parameters that have the most significant impact on the technological process of laser marking of textiles were worked out.*

Results. *The working intervals of the surface power density (*q_s*) for the various processes of laser marking at a speed of* v*Є[40÷140]mm/s for* CO_2 *and CuBr lasers have been defined. The maximum values of surface power density (*q_{Smax}*) for the studied materials at different focal length and diameter of the working spot have been calculated. The dependencies of the impact time (*t_{vd}*) from the laser beam speed in pulse mode have been received.*

Scientific novelty. *A physical model of the process of laser marking of textile materials is presented. The limits of applicability of laser marking for cotton and polyester fabrics have been defined.*

Practical value. *The optimal values (working intervals) of the main factors of the laser marking process have been obtained.*

Keywords: *Laser marking, cotton, polyester,* CO_2 *laser, CuBr laser, working intervals.*

Introduction. Marking with laser radiation is the process of modifying the surface when concentrated, coherent and monochromatic, high-intensity electromagnetic energy from a light beam is directed to the material [1, 2, 3, 4]. The impact is effective when the laser beam acts with a great power density (108÷1011 W.m^{-2}) and a duration of impulses between 10ns÷10μs on the treated area. As a result of the focus of the beam the heat is very intense in a small area. The resulting "mark" has a micro size of 20÷200μm [5]. Laser marking of textiles allows the creation of a unique, indelible mark that contains important information about the product.

For the organic polymers, such as textile polymers, the thermal influence of the laser radiation is expressed in an increase of the textile fibres' temperature to a temperature at which one or other processes take place and cause changes in their chemical and/or physical properties. Depending on the type of material and the reached temperature, laser marking happens as a result of one or more processes: destruction, depigmentation (discoloration), change in color, burning (carbonation), melting, evaporation, etc.

Destruction is the process of demolition of the cellulose polymer chain that builds up the cotton fibres. This demolition is caused by the thermal action of the laser radiation. In the cotton cellulose, destruction occurs in the range between 150^{0}C and 180^{0}C [6].

Decoloration (depigmentation) is another method used as a result of the thermo-effect by the impact of the laser which leaves a noticeable mark to the raw surface. The color fading or the complete removal of the color as a result of the controlled action of the beam on the dyed textile materials are caused by the photo-decomposition of the colouring agent (dye) without damaging the fibers of the basic textile material. During this process, the laser radiation penetrates into the polymer to a depth up to 100μm and is absorbed by the colored pigments [7, 8, 9]. The formation of a foam-like structure is a partial degradation of the material and it creates gas bubbles, the inside of which is filled with air or gaseous monomers. They have a depth up to 100μm in material and up to 50μm in height above the surface of the material. The bubbles become visible due to the differing refraction of the light [10]. *Re-crystallization* is a process of phase transformation of material from solid into liquid and then solid again as a result of which the color of the material changes. The process of vitrification occurs in the textile fibres and they pass from a high elastic into a pseudo-plastic state. For the cotton, the glass transition temperature is about 220^0C and for the polyester $80\div90^0$C. The polyester fibres melt at 260^0C.

Evaporation (ablation) occurs when heating the material above the temperature of evaporation, when the phase conversion of the surface layer (with a thickness ranging from parts of micron to several hundred microns) starts conversing from liquid or solid (sublimation) into gaseous form. As a result, channels are formed and a relief is observed. If another layer (for example coating) is put onto the fabric, through the laser treatment only this layer can be removed and channels can be formed with a color different from the color of the basic material. The polyester fibre is destroyed upon reaching 350^0C.

Carbonisation is an easy and effective way for laser marking in which a burnout takes place on the surface of the cotton textile products. The cotton fibres become carbonized at 300^0C. The mark has a yellow-brown color [11]. Marking through carbonation forms images with high and clear contrast, but there are also undesirable results: a part of the surface of the material can be destroyed and this reduces its resistance to wear. For this reason, it is necessary to determine the values of the parameters of the process very accurately and set boundaries of the area of application.

The mark is formed as a result of destruction, vitrification and carbonation for the cotton fabrics and vitrification, melting and evaporation for the polyester fabrics.

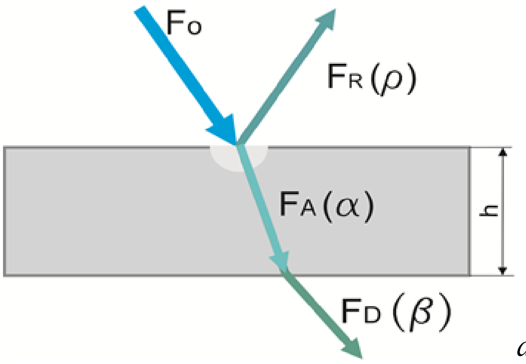
Objectives. When marking textile materials, it is not necessary to use a powerful laser radiation. It is necessary to achieve an optimal mode of the technological process by specifying values for the parameters of the laser system, under which it will be possible to obtain a mark with visible contrast without damaging the material and at minimal cost. In this study, in order to understand the physical nature of the process of laser marking of textile polymers, the interaction of the laser radiation with the substance of the treated material was analyzed and the limits of applicability of the physical model were defined. The aim was to work out the relationships between the physical magnitudes and to make some preliminary calculations in order to analyze their importance for the optimization of the laser marking of cotton and polyester textile materials with a view to achieve optimal quality of marks.

Research results. Processes in the material depend to a large extent on the optical and thermophysical characteristics of the treated material. A part of the light flow (F) which falls on the processed material is reflected by its surface (F_R), another part is absorbed (F_A), and a third part passes through material (F_D), where the respective coefficients are: ρ-reflection, α-absorption and β-transmission (Fig.1a). This can be expressed through the energy and will have the following form (Formula 1):

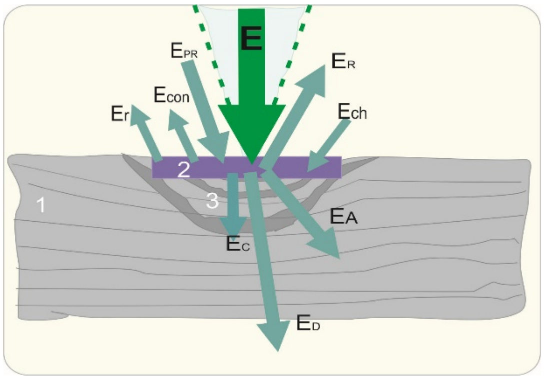
$$E = E_R + E_A + E_D \tag{1}$$

where: E - energy of the drop-down light flow, E_A - energy of absorbed light flow, E_R - energy of reflected back light flow, E_D - energy of transmitted light flow.

In the interaction of the laser beam with the material (Fig. 1b), in the area of processing 2 extra energy is also received as a result of the conduct of other possible processes such as: E_{ch} - chemical reactions (oxidation), E_c - energy which moved to the heat-affected zone around the work area 3, E_r - energy of the radiation emission, E_{con} - loss of energy by convection, E_{PR}- technological process energy (energy for heating, melting and/or evaporation) [12].



а)



в)

Fig. 1a. **Beam falling over the textile material** **Fig. 1b. Physical model of the process of laser marking of textile materials - energy balance**

The energy of the laser beam - E that falls on the textile material is transformed into different energies and the equation of the energy balance can be written:

$$E = E_A + E_R + E_D + E_{PR} + E_{ch} + E_c + E_r + E_{con} \tag{2}$$

The loss of energy by convection E_{con} and the energy of radiation emission E_r are negligible, as the heating of the material takes place for a very short time followed by cooling for almost the same time. As a result of the heat conduction of the material, the heat spreads deeply in the product, but the heat-affected zone is small because the time is short and the E_c values are small. As a result of the reflection from the surface, energy losses E_R are received and a part of the energy is wasted by its passage through the fabric - E_D. Taking into account the loss of energies, the following equality can be written for the energy required for the marking of the material:

$$E_A + E_{ch} = E_{PR} + E_c \tag{3}$$

The process of laser marking of textile polymers is complex and in its realization, influence of a multitude of technological factors and physical quantities is observed in varying degrees [13]. In order to evaluate the extent of the impact of each of them, it is necessary to analyse these factors and variables, the links between them and their correlations. In this paper, the factors with the greatest impact on the process and the most essential links between them are presented. The surface power density - q_s, is a major technological parameter that determines the quality of the laser marking process and the contrast of marking. It depends on the average power of the laser source - P and the area of the beam – S:

$$q_s = \frac{\mathrm{P}}{\mathrm{S}} = \frac{4.\mathrm{P}}{\pi.\mathrm{d}^2}, W.m^{-2} \tag{4}$$

$$q_s = f\,(P, d_f) \tag{5}$$

For each laser, the maximum power is specified by the manufacturer and cannot be changed. Therefore, the optimization of this parameter will depend on the size of the circle with diameter d_f, formed by the laser beam and called focal spot (5). The change of the focal spot diameter will cause a change of the surface power density. At the same average power of radiation, the smaller the area onto which the beam is focused, the bigger will be the value of q_s. The relationship between the critical power density $q_{s\,кр}$, and temperature T is given by the equations (6):

$$q_{s\,kp.} = \frac{(\mathrm{T}-T_0)k\sqrt{\pi}}{2(1-R)\sqrt{a.t_{\mathrm{vd}}}} = \frac{(\mathrm{T}-T_0)k}{2.A}\sqrt{\frac{\pi.\mathrm{v}}{a.d_f.\tau.\upsilon}} \qquad (6) \qquad\qquad t_{\mathrm{vd}} = \frac{d}{\mathrm{v}}\tau\upsilon \qquad (7)$$

$$q_{s\,kp.} = f\ (T, A, k, a, d_f, \tau, \upsilon, \mathrm{v}) \qquad (8)$$

For the process of laser marking, the surface power density q_s is associated with almost all parameters of the technological system (6 and 8): t_{vd} - time of impact of a laser in pulse mode (7), k - coefficient of thermal conductivity, α - coefficient of absorption, R - reflection, A- absorption, v - marking speed, d_f - diameter of focal spot, υ - frequency of repetition of impulses, τ - duration of impulses. The critical values of the surface power density are important for the differentiation of the ongoing processes at: different speeds of marking - v_i, different lasers - L_i and different types of textiles. The minimum diameter of the focal spot d_f is calculated for both types of lasers (L_1- CO_2 and L_2 - CuBr) and focal length f_i. The results are summarized in Table 2. From the theoretically calculated values for d_f at different focal length and diameter of the pull-down radiation, the most suitable laser system can be chosen.

Table 2

Minimum diameter of the focal spot at the focal length f_i

D mm	d_f, μm							
	f_1 = 100 mm		f_2 = 160 mm		f_3 = 254 mm		f_4 = 300 mm	
	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2
8	253,2	13,8	405,1	22,1	643,1	35,1	759,6	41,5
9	225,1	12,3	360,1	19,7	571,6	31,2	675,2	36,9
10	202,5	11,1	324,1	17,7	514,5	28,1	607,6	33,2

The maximum value of q_{Smax} is calculated by the formula (6) and the values for d_f are taken when the diameter of the drop-down radiation on the lens is D=10*mm* (*Table* 3).

Table 3

Maximum power density at the focal length f_i

Laser	P, W	d_{f1}, μm	$q_{s\,\max 1}$ $10^8 W.m^{-2}$	d_{f2}, μm	$q_{s\,\max 2}$ $10^8 W.m^{-2}$	d_{f3}, μm	$q_{s\,\max 3}$ $10^8 W.m^{-2}$	d_{f4}, μm	$q_{s\,\max 4}$ $10^8 W.m^{-2}$
	$f_{i,\,mm}$	$f_1 = 100$		$f_2 = 160$		$f_3 = 254$		$f_4 = 300$	
L_1	50	202,5	15,5	324,1	6,07	514,5	2,41	607,6	1,73
L_2	10	11,1	103,4	17,7	40,7	28,1	16,1	33,2	11, 6

In order to take into account the influence of the temperature, which is transmitted to the workpiece material by the laser beam, the critical power density is calculated by the formula (6), where the focal length f_2=160*mm* for marking of cotton (C) fabrics by: destruction ($q_{Sкр.д}$), vitrification ($q_{Sкр.в}$), carbonation ($q_{Sкр.к}$) and for marking of polyester (PET) fabrics by: vitrification ($q_{Sкр.в}$), melting ($q_{Sкр.т}$), evaporation ($q_{Sкр.и}$).

From the calculated values for the critical power density and maximum power density q_{Smax}, intervals for the power density in the marking with L_1 (CO_2 with λ_1=10,6μm) & L_2 (CuBr with λ_2=0,511μm) lasers are received, through the various stages of the process, for cotton and polyester materials respectively Tables 4 and 5. The values of the temperature - Ti, are taken for the respective conditions of the material when heated.

Table 4

Intervals for the power density for cotton materials with L_1 & L_2

№	*v*, mm/s	q_S, 10^8 W.m^{-2}					
		Destruction		Vitrification		Carbonation	
		L_1	L_2	L_1	L_2	L_1	L_2
1	40	1,15÷ 1,77	4,9÷7,6	1,77÷2,48	7,6÷10,7	2,48÷6,07	10,7÷40,7
2	65	1,47÷ 2,26	6,3÷9,7	2,26÷3,16	9,7÷13,6	3,16÷6,07	13,6÷40,7
3	90	1,73÷ 2,66	7,4÷11,4	2,66÷3,72	11,4÷16,0	3,72÷6,07	16,0÷40,7
4	115	1,95÷ 3,00	8,4÷12,9	3,00÷4,20	12,9÷18,1	4,20÷6,07	18,1÷40,7
5	140	2,15÷ 3,31	9,2÷14,2	3,31÷4,64	14,2÷19,9	4,64÷6,07	19,9÷40,7

Table 5

Intervals for the power density for polyester materials with L_1 & L_2

№	*v*, mm/s	q_S.10^8 , W.m^{-2}					
		Vitrification		Melting		Evaporation	
		L_1	L_2	L_1	L_2	L_1	L_2
1	40	0,54÷ 2,16	2,32÷9,27	2,16÷2,96	9,27÷12,75	2,96÷6,07	12,75÷40,7
2	65	0,69÷ 2,75	2,96÷11,82	2,75÷3,78	11,82÷16,26	3,78÷6,07	16,26÷40,7
3	90	0,81÷ 3,23	3,48÷13,91	3,23÷4,45	13,91÷19,13	4,45÷6,07	19,13÷40,7
4	115	0,91÷ 3,65	3,93÷15,72	3,65÷5,03	15,72÷21,60	5,03÷6,07	21,60÷40,7
5	140	1,01÷ 4,03	4,34÷17,35	4,03÷5,54	17,35÷23,90	5,45÷6,07	23,90÷40,7

The resulting graphic dependencies (Fig.2) for $q_{sкр.i}=f(v_i)$ are almost linear and with the increase of the speed, the surface density of power also increases. When marking by carbonization of cotton materials for both lasers, it can be seen that for L_2 almost five times higher qs is needed than with L_1 laser under the same conditions of the technological process of marking. When marking of polyester material by evaporation for both L_1 and L_2 lasers, the dependencies show almost the same as with the cotton materials dependencies, but the L_2 curve is slightly less steep.

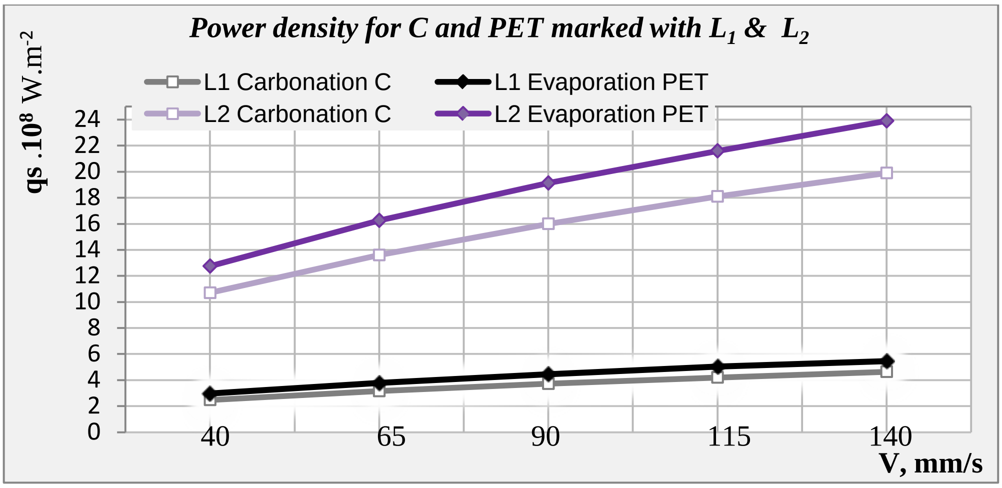


Fig.2. **Dependencies of the power density from the speed $q_{s\ кр.}$=f(v) when marking of cotton and polyester materials with L_1 and L_2 lasers**

If we compare the two lasers and both materials (C and PET), when marking by carbonation and evaporation respectively, there is a greater value of curves for the marking of polyester materials compared to cotton materials and it is more expressed when marking with laser L_2.

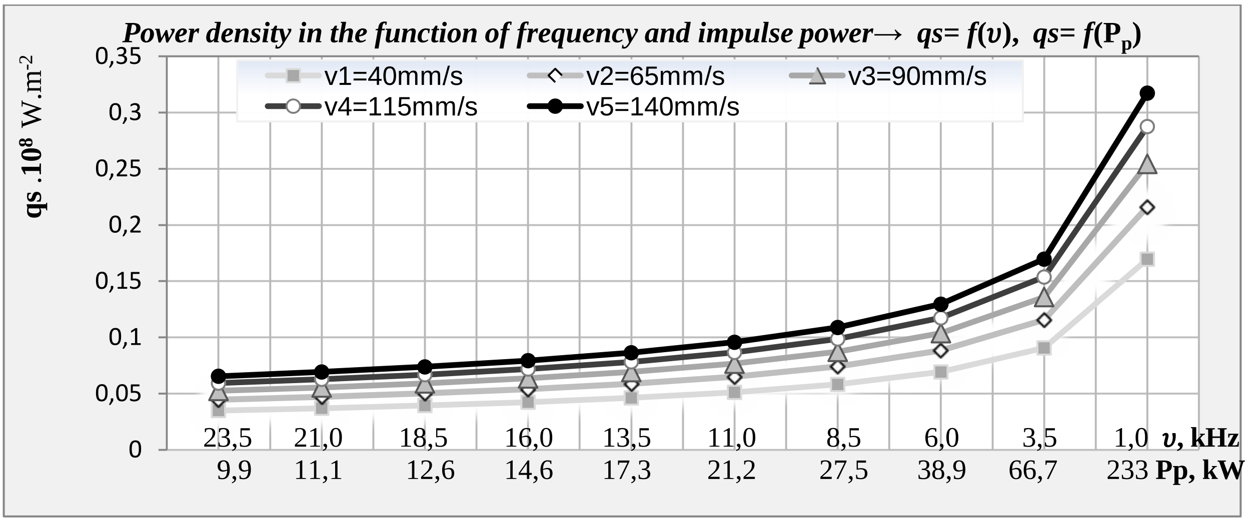


Fig.3. **Dependencies of the power density from the frequency of the laser pulse and the impulse power for L_2**

This can be explained by the different wavelengths of the two lasers. When marking with L_2 laser, even at lower speeds, the power density necessary for the realization of marking with good contrast will be reached. The results of the change of the surface density of power at the change of frequency in the range 1÷24kHz (impulse power - P_p respectively) for laser L_2 at various speeds of the laser beam are shown in Fig. 3. The relationship between the pulse power and the frequency of pulse is inversely proportional, allowing even at a low pulse power to reach significant values of the frequency of pulse.

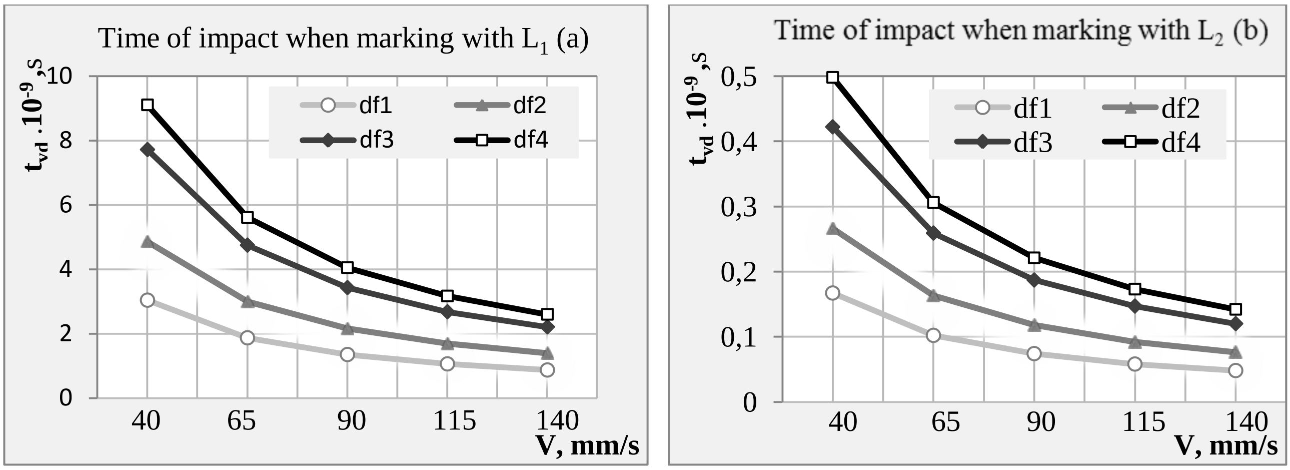


Fig. 4. **Time of impact (t_{vd}) when marking with L_1 (a) and L_2 (b) lasers and different d_f**

The graphics in Fig. 4 show the dependence of the time of impact t_{vd} of the laser beam from the increase of speed for the different diameters of the focal spot. The comparison of the graphs for the two lasers shows that the dependence between the time of impact and the speed of movement of the laser beam, in the pulse mode of the laser system, is nonlinear. With the increase of the speed, the time of impact decreases for both lasers. As much the speed is higher, the less it depends on the diameter of the focal spot. It can be seen clearly that the time required for the impact on the material with the laser L_2 is in times less compared to the laser L_1. This means that if the laser with vapours of copper bromide is applied, under the same parameters of the technological process, productivity would be higher.

Conclusion. From the calculations and the relevant graphics, it can be concluded that when increasing the speed of marking, the amount of the absorbed energy increases and therefore the productivity of the technological process of laser marking of textiles will also increase.

On the other hand, when the speed is higher, the time of impact of the laser beam on the processed material will decrease. If working with smaller speeds, the laser beam will stay for a longer time on the marking field and will absorb a greater amount of energy. As a result of this, a bigger contrast of the marking will be achived.

The presence of the two contradictory conclusions is an opportunity to search a compromise between productivity and quality. For the textile polymers of organic origin, if the surface density of power is greater than a certain critical value - $q_{s\ кр.}$, the demolition of the fibres, and the fabric in general, can happen very quickly.

From the above follows that, when marking textile fabrics, the most important condition for achievement of a high contrast is the determination of the optimal values of the relevant parameters of the process, including the power density, as the main parameter, and the speed of the laser beam in its movement on the material.

In this study, the limits of the applicability of laser marking of cotton and polyester fabrics with two types of lasers have been determined. The working intervals of the surface power density for the various processes of laser marking at a speed of v€[40÷140]mm/s for CO_2 and CuBr lasers have been defined. The maximum values of the surface power density for the investigated materials have been calculated. The dependencies of the impact time from the speed of the laser beam in pulse mode have been received. The obtained results allow expanding the practical application of this innovative technology in the textile industry.

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ОПРЕДЕЛЕНИЕ КРИТИЧЕСКИХ ЗНАЧЕНИЙ УДЕЛЬНОЙ МОЩНОСТИ ПРИ ЛАЗЕРНОЙ МАРКИРОВКЕ ТЕКСТИЛЬНЫХ МАТЕРИАЛОВ

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Цель. *Определение пределов использования лазерной маркировки хлопчатобумажных и полиэфирных тканей с использованием двух типов лазеров:* L_1 - CO_2 *и* L_2 - CuBr.

Методика. *Цифровые данные, полученные в результате экспериментального исследования, систематизировали и обрабатывали аналитически, и результаты представлены графически. Разработаны зависимости между физическими параметрами и параметрами, которые оказывают наиболее существенное влияние на технологический процесс лазерной маркировки текстиля.*

Результаты. *Определены рабочие интервалы поверхностной удельной мощности* (q_S) *для различных процессов лазерной маркировки со скоростью v [40 ÷ 140] мм / с для лазеров на* CO_2 *и CuBr. Рассчитаны максимальные значения поверхностной удельной мощности* (q_{Smax}) *для исследуемых материалов при различном фокусном расстоянии и диаметре рабочего пятна. Были получены зависимости времени воздействия* (t_{vd}) *от скорости лазерного луча в импульсном режиме.*

Научная новизна. *Представлена физическая модель процесса лазерной маркировки текстильных материалов. Определены границы применимости лазерной маркировки для хлопчатобумажных и полиэфирных тканей.*

Практическая значимость. *Получены оптимальные значения (рабочие интервалы) основных факторов процесса лазерной маркировки.*

Ключевые слова: *лазерная маркировка, хлопок, полиэстер, CO_2-лазер, лазер CuBr, рабочие интервалы.*

ВИЗНАЧЕННЯ КРИТИЧНИХ ЗНАЧЕНЬ ПИТОМОЇ ПОТУЖНОСТІ ПРИ ЛАЗЕРНОМУ МАРКУВАННІ ТЕКСТИЛЬНИХ МАТЕРІАЛІВ

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Мета. *Визначення меж застосування лазерного маркування бавовняних і поліефірних тканин з використанням двох типів лазерів: L_1 - CO_2 і L_2 – CuBr*

Методика. *Цифрові дані, які отримані в результаті експериментального дослідження, систематизували та обробляли аналітично, і результати представлено графічно. Розроблено залежності між фізичними параметрами і параметрами, які мають найбільш істотний вплив на технологічний процес лазерного маркування текстилю.*

Результати. *Визначено робочі інтервали поверхневої питомої потужності (q_s) для різних процесів лазерного маркування зі швидкістю v [40 ÷ 140] мм / с для лазерів на CO_2 і CuBr. Розраховані максимальні значення поверхневої питомої потужності (q_{Smax}) для досліджуваних матеріалів при різній фокусній відстані і діаметрі робочого плями. Були отримані залежності часу впливу (t_{vd}) від швидкості лазерного променю в імпульсному режимі..*

Наукова новизна. *Представлено фізичну модель процесу лазерного маркування текстильних матеріалів. Визначено межі застосування лазерного маркування для бавовняних і поліефірних тканин.*

Практична значимість. *Отримано оптимальні значення (робочі інтервали) основних чинників процесу лазерного маркування.*

Ключові слова: *лазерне маркування, бавовна, поліестер, CO_2-лазер, лазер CuBr, робочі інтервали.*