Laser marking system for plastic products

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***Abstract* — This research paper solves the challenge of plastic product marking. In particular, plastic cap marking. Nowadays, IR lasers (fiber, solid-state, gas lasers) are used for plastic marking, in most cases these are 1.06 µm fiber lasers, but plastics must contain metal additives for obtaining a high-quality marking with such a laser. And those additives are not safe for plastic products in the food industry. This problem is solved by using high-energy UV lasers. Therefore, the NII Laser Technology PJSC team has developed and produced a comprehensive system for high-resolution marking of both plastic products and other materials (metal, glass, ceramics) based on an ultraviolet laser. A combination of 2D-scanning technology, adaptive focusing, marking of objects in motion (on-the-fly), as well as a number of other technological and design solutions in this system made it possible to start production of conveyor lines for dynamic marking of beverage closures, crown caps, elongated plastic and metal caps amongst others that are used in the food industry. In comparison to the existing marking technologies, the developed laser marking comprehensive system provides high-speed (up to 100 thousand caps per hour) marking with text, digital and graphic data on the outer surfaces of the plastic produced without any special coloring agents, and allows getting a contrast image by using gray shading regardless of the surface color. At the present day, NII Laser Technology PJSC has carried out work to expand the capabilities of the laser marking comprehensive systems through the introduction of 3D scanning technology and the use of two band laser systems, that increase the product protection. The safety of using ultraviolet radiation for marking the internal surfaces of food packaging plastic elements is confirmed by the certificate on laboratory testing by INSTITUT NEHRING GmbH - Heesfeld 17-38,112 Braunschweig**

Keywords — laser, radiation, objective lens, frequency, speed.

I. Introduction

The effect of laser radiation on materials has been researched since the discovery of lasers. In connection with the constant technology development, lasers are most often used to process almost any material. Marking is a prospective line of development in the laser technology field due to its demand almost everywhere. In current times, metals, plastics, glass, polymers amongst others are the most promising products for scientific research on the interaction of radiation with a material. The marking concept and mechanisms that explain the essence of the process are still being studied. A variety of mechanisms and models explaining the essence of the interaction of laser radiation with a material is very wide [1-3], but so far no general systematics on the selection of parameters and explanations of what is happening inside the material depending on certain conditions have been found. Some kind of fundamentals and recommendations are needed to simplify the process when operating with different materials, but no such recommendations have been previously provided. Therefore, the purpose of this research paper is to develop a laser marking system for plastics, as well as to study their interaction with laser radiation.

II. Theoretical background

A large number of possible mechanisms and models for the destruction of materials of various classes under the action of laser pulses have been discussed in the literature since the beginning of research on the problem of laser interaction with materials up to the present. A general analysis of all available data for materials such as plastics, glass, precious stones and polymers was carried out. Local laser modification of solids can be caused by various mechanisms of laser radiation energy absorption according to the concept that has been established by now. Among them, there are so-called intrinsic mechanisms [3] associated with the properties of the matrix itself (collision and multiphoton ionization), which are possible only under the influence of ultrashort pulses; and mechanisms caused by absorbing defects (thermoelastic, photoionization, etc.), implemented in the long pulses area. The implementation of one or another mechanism of (thermal/non-thermal) destruction depends on a large number of factors: the purity of the samples studied, the radiation wavelength, the duration of the laser pulse, the pulse repetition rate, focusing parameters, etc. However, all of the mechanisms are often implemented. The extent of their impact on the process outcome is also different. In this regard, it is preferable to have the possibility to change the values of the specified radiation and focus parameters quickly from millimeters to femtoseconds [4-5], in order to determine the dominant mechanism of destruction for each particular case of material processing. At present, it is much more common to use lasers with a short radiation pulse duration (from the nanosecond range and below) to apply marks on the material surface, therefore we will take into account precisely these pulse duration values in the following. Based on the literature reports [6], three thermal models, that describe the interaction of laser radiation with a material, can be distinguished.

Case 1. Long pulses comparable to the relaxation time (less than 1 ms). It is characterized by photothermal ablation (heat propagates due to thermal conductivity) and evaporation of the material with boiling after the initial melting. However, such a thermal effect may cause the

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material removal. Non-thermal effects include mechanical stresses and photochemical ablation, i.e. in some cases, the photon energy is sufficient for the direct destruction of chemical bonds without heat input.

Case 2. Shorter pulses with thermal equilibrium still persist, but heat loss is directed towards evaporation (less than 1 ns). Both heating described by a quadratic function and cooling described by a logarithmic function occur with such an effect. Some steps within the description of this function are caused by hidden thermal effects. The processing by nanosecond pulses is based itself on the formation of plasma therein, as a result of which a gradual formation of an impact crater occurs.

Case 3. Ultra short pulses that are small compared with the relaxation times of the structure. Such an effect leads to non-thermal equilibrium with electrons and a lattice having different temperatures with direct evaporation and Coulomb effect (less than 1 ps). The essence of the process is to remove the material without significant heating of nearby areas. In this case, thermal concepts are not applicable. Thus, each case has its own patterns, which must be considered when processing materials.

If we talk about direct interaction with the absorbing medium, the luminous flux is partially reflected from the surface, and partially penetrates into the material being absorbed in it. The change in the density of the q light flux, i.e. the amount of light energy per unit surface of a material per unit of time in an absorbing medium is described by the Bouguer-Lambert law [7]:

$$q(x) \quad = q_0 A e^{-\int_0^x \propto(x)dx} \qquad (1)$$

where q_0 is the density of the incident light flux on the surface of the material; A - material absorption capacity; $\propto (x)$ is the coefficient of light absorption in the medium; x - the coordinate (counting from the surface into the material).

The specific values of A and $\propto$ variables included in the formula (1), as well as the mechanisms of light absorption and its transfer into heat, are different for all materials. For example, the values of the reflection and absorption coefficients depend on the radiation wavelength. Using formula (1), one can always theoretically check the level of input energy at given depths of the material, which is an integral part when planning and carrying out the experiments. However, it should be borne in mind that only linear absorption in a homogeneous material is taken into account, and the mechanisms causing the nonlinear behavior are neglected, when using the Bouguer-Lambert law.

The purpose of laser marking is to change the visual contrast. This can be achieved in two ways: either by changing the color or by changing the reflections. Almost all types of lasers can be used for marking. For example, pulsed TEA CO2 lasers (10 W, 70 ns) [8] are widely used to mark to beer bottles with logos. If we talk about the diameter of the spot, it is below 80 microns in some laser systems, which is the visual threshold for the unaided eye. Such small spots are often used in machine-readable systems. The use of such a small spot diameter for eye-readable codes is possible if several lines are used to increase the width. Additional lines increase the resulting marking time. Special long-focus lenses or telescopes are used to reduce the processing time, which leads to an increase in the spot size.

The type of the image being marked, its design and quality, the item type, the requirements for operation and the material type should determine both the type of laser and the laser beam positioning systems used in it. As a rule, one of the following systems is used: polygon systems (polygon mirrors), projected masks (fixed and program-controlled masks), and beam re-reflection systems (mechanical or optical laser beam scanning system). Summarizing the results, it should be noted that each of the lasers and the systems used with them have been studied for a number of years, but some unexplored areas still remain.

Let us consider the marking of plastic material in more detail. A variety of plastics is ideal for being processed with laser radiation in terms of selecting the wavelength, which can both be absorbed and pass through completely. Due to the possibility of focusing radiation into a small-seized spot and a high concentration of energy, one can reduce the treated area when marking, and the quality of the obtained labeled layer improves accordingly, but its dependence on the product thickness remains to be a rather important factor [9]. Polymers can be marked in several different ways using lasers (ablation, carbonization, melting, discoloration, etc.). These processes are based on a change in the polymer structure through any change in the position of carbon in the molecular structure. Local changes in the structure and properties occur under the influence of both the laser radiation of a certain wavelength and the energy in the material, which are necessary for the subsequent registration of the changes that have occurred to the irradiated material. The impact area is chosen to be as small as possible, but at the same time sufficient for its detection by the technical means used for the marking. The material under the impact of wavelengths, that have, as a rule, the UV range and don't relate to visible light, as well as to publicly available radiation sources, changes the optical properties (transmission coefficient) in these areas. But the detection of the properties change effect cannot be made directly, since one needs some additional values for comparison in order to identify it. It is possible to obtain a whole image or pattern by applying a set of points in a certain order. When an electromagnetic wave has passed through the material, the energy of the excited oscillations can be partially transferred into the internal energy of the material or into the secondary radiation energy, that has a different spectral composition or a different direction of propagation, which leads to the absorption of a light wave. This effect is also described by the Bouguer – Lambert law (1) and it is valid for not very powerful radiation sources. All translucent materials with their ideal highly coherent microstructure and the absolute absence of impurities have their own fundamental light absorption. The electron shells of molecules are excited when light is absorbed in the UV and visible parts of the electromagnetic wave spectrum. The absorption is accompanied by the transition of the molecule from a state with lower energy to a state with higher energy. The excitation energy of the electron shell of a molecule has much greater magnitude, than the excitation energy of its vibrations. In molecules, each electronic level corresponds to a set of vibrational-rotational levels. The electronic transition is always accompanied by a change in the vibrational-rotational state of the molecule, which leads to the appearance of wide bands in the absorption spectrum. The position of each band is determined by the energy difference between the electron levels of the molecule. Photons are absorbed when polymer molecules interact with light fluxes, and it provokes the development of photochemical transformations. Photo- and photochemical destruction of polymers proceeds under a mechanism close to the well-studied radical mechanism of hydrocarbon oxidation.

Ablation, marking with the additives, oxidation, melting, carbonization, foaming, discoloration, flowering, dehydration amongst others can be distinguished as the main methods for plastic product marking. A specific type of laser and parameters were chosen for each of them. For example, both 355 nm wavelength and about 15 ns pulse width are used for marking, which is carried out by means of foaming and discoloration at the same time, and 1064 nm wavelength the material processing is carried out by foaming, melting or marking with additives if there are any, but the presence of additives in the plastic products of the food industry may adversely affect the life and health of the consumer. Therefore, it makes sense to use UV lasers for plastics in the food industry.

In the future, mid-IR fiber lasers [10-11], as well as lasers of a new generation, which are micro- and nanolasers [12-13], can be used as radiation sources for marking.

III. LASER MARKING SYSTEM

Laser technologies can solve the problems associated with the limitations of inkjet printing on the inner surface of the closures, as well as replace the pad printing technology on the outer side of the products if only one color in shades of gray is used. The following solution, which is shown in Fig. 1, is chosen as a modern technical solution of the optical part of the system, that allows you to perform tasks for printing dynamically changing images.

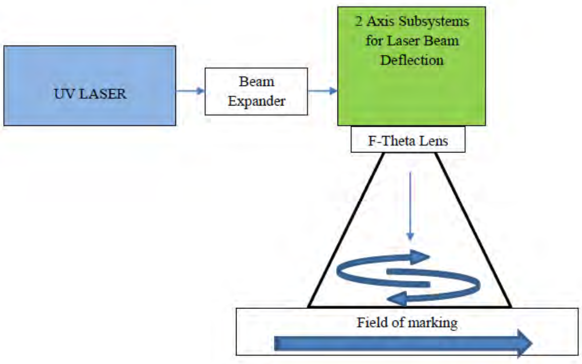

Fig. 1. The building-up principle for the optical part of the dynamic product marking system.

The following scientific, technical and structural problems were solved when developing laser marking comprehensive systems:

- ensuring the specified parameters of laser radiation for different samples in order to obtain a contrast marking by optimizing the energy and frequency characteristics of the laser, as well as changing the radiation focus parameters on the item surface with a constant geometric marking field;

- optimization of time spent on the selected image marking;

- ensuring the marked surface location relative to the optical axis of the 2D laser beam scanning system with a given error;

- ensuring the controlled moment of the item feeding, the marking process initiation and tracking the marked part in motion (on-the-fly) on a conveyor belt in real time mode;

- minimization of mechanical pauses between markings, in order to improve the system productivity;

The block diagram model of the laser marker shown in Fig. 2 was substantiated as a result of solving these challenges.

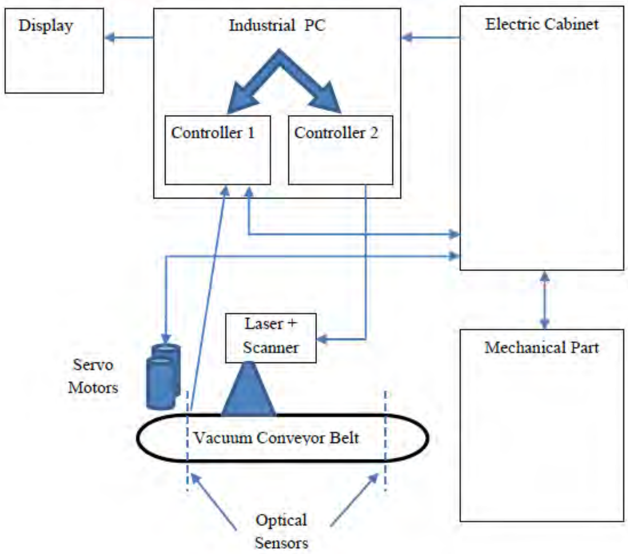

Fig. 2. The block diagram model of the laser marker.

A 15 or 30 W 355 nm laser with 50-100 kHz frequency and 15 ns pulse width is used as a radiation source. A double-axis scanner with a F-Theta lens, 160x160mm work field and 50 - 100 µm radiation focusing spot was used as a laser beam scanning system. High resolution and marking performance are both achieved due to these parameters of the marking system optical elements. The marking system of plastics developed according to the proposed block (Fig.2) diagram is shown in Fig. 3.

Fig. 3. The marking system of plastics

IV. RESULTS AND DISCUSSION

The study to determine the possibility of marking application and identifying the impact time was carried out on an ultraviolet laser operating at 355 nm with 15-30 W average radiation power and 10-15 ns pulse width. The time of impact on one point was determined by an experimental method taking into account appearance of visible changes, which consist in lightening the color of plastic or foaming, Fig. 4.

Fig. 4. UV laser marking on plastic closures.

But there are also problematic directions of marking with UV laser. These are transparent plastics that are fully-transparent for 355 nm wavelength. Marking by lightening and foaming are not applicable to such plastics, the only option is fusing, Fig. 5, but the marking quality and speed characteristics of the entire laser system will be very poor, apart from that, the safety requirements of use in the food industry are not met.

Fig. 5. Transparent plastic marking

Fig. 6. An example of high-quality marking on bronze colored caps.

The experiments showed, that also silver and bronze colors are problematic in terms of UV laser marking of plastic materials. The challenge was solved by increasing the marking speed and increasing the image focus spot diameter from 50 to 100 µm, Fig. 6.

According to the results of the experiments, it was determined that marking by lightening and foaming with the minimum release of substances harmful to the food industry is carried out using a laser with 355 nm wavelength as the best option.

V. CONCLUSIONS

The proposed and implemented technologies of laser marking for the food industry are an alternative to the traditionally used pad and inkjet types of printing. Laser technologies allow to overcome the existing limitations of traditional printing methods, to improve product quality and to create new tools used in the process of manufacturing closures. 355 nm lasers are best match for the food-grade plastic product marking. The safety of using ultraviolet radiation for marking the internal surfaces of food packaging plastic elements is confirmed by the certificate on laboratory testing by INSTITUT NEHRING GmbH - Heesfeld 17-38,112 Braunschweig in 2015.

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