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Valentyn OSYPOV
National Transport University
M. Omeljanovich-Pavlenko str., 1, 02000 Kyiv, Ukraine
Corresponding author. E-mail: osipov.valentin100@gmail.com

DEVELOPMENT AND IMPLEMENTATION OF RETRO-REFLECTIVE ELEMENTS FOR AUTOMATIC ACCESSORIES AND PLACES OF PLANNED POINTS

Summary. For the first time, it was proposed to develop an optimal design of a circular reflector, to modernize the equipment for the production of a special cutting tool, and to work out the technology of formation with its use of the matrixes of the originals of the retro-reflective elements, and the technology of galvanic cultivation of precision working matrix dies.

1. INTRODUCTION

Today, in Ukraine, high-technology approaches are widely used in various sectors of the economy. One of these areas is the creation of high-performance microprismal retro-reflective elements. Such items are becoming more and more used, particularly in the transport, road and other industries [1].

The use of various optical retro-reflective devices, which include road signorientation, columns, separating strips and other engineering equipment of highway with retro-reflective elements, can significantly improve driving conditions and night traffic safety, as all road signs with modern high-performance retro-reflective elements become noticeable at a fairly long distance [2-5].

However, the use of modern retro-reflective materials in our country is still not enough, because all these fairly valuable retro-reflective elements and materials are now procured from abroad. As a matter of fact, the production of retro-reflective materials in Ukraine is absent, although today several domestic companies that produce road signs using original materials from 3M and other foreign manufacturers, in particular from China and Poland, are active in the transport market of the country.

Therefore, the task of organizing the industrial production of own retro-reflective materials and elements becomes important. To do this, you need to complete a complex mesh of scientific and applied research on the creation of modern light-reflective materials, to develop a technology for the creation of such materials and to design and manufacture special equipment and tools for the release of finished products.

It is proposed to develop the optimal design of the circular reflector, to modernize the equipment for the manufacture of a special cutting tool, and to work out the technology of forming it with the use of the matrixes of the originals of the retro-reflective elements, and the technology of galvanic cultivation of precision working matrix dies.

2. ANALYSIS OF THE MEANS OF INCREASING THE SAFETY OF TRAFFIC IN THE DARK TIME OF DAY, SUFFICIENCY OF THE NOMENCLATURE OF SUCH MEANS

The purpose of the work is to develop, manufacture and implement competitive high-tech modern products - microprismal retro-reflective elements - for the provision of motorways, transport networks and solutions for the purpose of increasing safety during the dark hours of the day.

In addition to horizontal and vertical road markings, there are the so-called "auxiliary tools" - road marking insert (RMI) - to traditional technical road traffic control devices that have an impact on road safety in adverse weather conditions and at night.

IMR products are intended to improve the visual orientation of the driver on the travel section and can be used independently or along with the horizontal road marking, which is more often used. The operation of the IMR is regulated by the State Standard of Ukraine DSTU 4036-2001 "Inserts marking road. General technical requirements".

However, the current IMR nomenclature does not fully meet the needs for equipping highways with safety enhancements. The issue of equipment with these means of ring roads and streets in one level remains unresolved. Due to the special geometric parameters of this kind of intersections, there is a need for the use of a special form of ring gear, which in turn should facilitate the visibility of the entire object at the same time, and in advance provide the driver with information about the form of the obstacle that awaits him in front. Due to the fact that, as a rule, a road ring is arranged with the use of a curb, the possibility of installing other than the other types of WFD directly on the curb should be considered. This will solve such issues as preventing deformation during the accidental ride of heavy transport and deformation of the IMR during the winter clearing of the roadway from the snow by specialized equipment.

It is known [1] that an increase in the use of retro-reflecting elements of a distance at which a driver becomes noticeable during the movement of a car, from 25-40 m to a distance of 300-400 m, reduces the potential risk of a car ride on it in the dark by almost 7 times.

To implement the project, it is necessary to develop and implement technological processes and precision equipment for the production of curbs of circular microprism retro-reflective elements:

- to develop and implement technological processes and precision equipment for the production of highly effective polymeric microprism retro-reflecting elements of round shape;
- to develop and implement technological processes and equipment for the manufacture of bodies of light-reflective structures of structural plastics;
- to develop and implement technological processes and equipment for collecting elements and sealing of retro-reflective microprism structures.

3. DETERMINATION OF REQUIREMENTS FOR RETRO-REFLECTING ELEMENTS

When developing modern light-reflecting elements, the main problem is to increase the efficiency of light reversal [6]. The most perfect today's retro-reflective materials are the structures in which the reflective surface consists of a system of reflectors - microprisms, formed by one way or another on the forming surface. Light efficiency of such a retro-reflective element with microprisms is directly related to the phenomenon of "complete internal reflection of light" [7], well known to physicists. The process of light reversal is due to the threefold reflection of a beam of light from three mutually perpendicular faces of these reflectors.

Nowadays, in the market of microprism oscillations, elements with a reciprocation factor for some distances up to $R(\varphi_0)$=800-900 cd/lux.m^2 are common in the market of microprisical cataclysms; therefore, the requirements for the equipment and instrument for the manufacture of originals of such devices are high too. To obtain the maximum possible return ratios $R(\varphi_0)$, the tolerances on the corners between the reflecting faces of the microcubes must not exceed several angular seconds, and the roughness of the light-receiving faces should not be worse than 0.05 microns.

These parameters are primarily ensured by the high quality of the cutting diamond tool, with which the matrix-originals of the retro-reflective elements are produced. The faces used for cutting the microrelief of the diamond cutter must correspond to class 14 of surface cleanliness, that is, they are missing at times, deeper than 25-50 nm at the base length L_B=0.08 mm.

The optimally designed and carefully manufactured elements are capable of reflecting the incident beam at a distance up to several hundred meters. For example, today's US technical standards for the light characteristics of the elements normalize the value of the reciprocation factor $R(\varphi 0)$=700cd/(lux

m^2) for the observation distance LH=800 m. It is precisely these elements of their parameters that were supposed to be developed and made in the process performance of the specified work.

For the realization of the tasks of this work, the so-called "symmetric" microprism retro-reflective elements are found to be most suitable, for which the angle reversal angle is symmetric with respect to the normal to the forming surface. For traditional symmetrical retro-reflective elements, the groups of microcubes are located on a flat-forming surface in the form of tetrahedra with angles in the base (60°-60°-60°). The angle of inclination of each of the three lateral faces of each microtitrade to its axis is θ_0=35º15'52". The effective surface $S_e(\varphi_0)$ of the symmetrical retro-reflective element, that is, the ratio of the reciprocal surface to the full surface of such a reflector, for the angle of incidence of the beam φ_0=0, is 67%. The reciprocation diagram is symmetric with respect to the zero angle of illumination φ_0=0, that is, perpendicular to the forming surface.

3.1. Determination of requirements to the light characteristics of retro-reflective elements

In accordance with the State Standard of Ukraine 4036-2001, the light-reflection coefficient of microprism retro-reflective white-colored elements must be at least 250 cd/(lux cm^2), with the observation angle φ_C=0,2º and the angle of illumination φ_0=4,0º.

The magnitude of this coefficient is influenced, above all, by the quality of the surfaces of the microcubes on the forming surface of the element. Therefore, in the manufacture of originals of light-reflecting elements by the diamond cutting method [8], extremely high demands are placed on the diamond cutting tool used to make original matrices, and on the positioning system of the cutter at the microrelief formation station which controls the movement of the diamond cutter during the microrelief cutting. However, an important factor is also diffraction of light on a regular structure that the microrelief surface of the light reflector is. For the first time, the role of light diffraction on the periodic microcube reflective structure in the formation of the energy diagram of light-reversal was considered in a publication [9]. The calculated reciprocation diagram from the work [9] of the microcube with curved surfaces is depicted in Fig. 1.

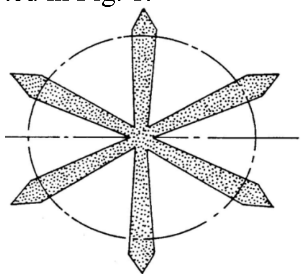


Fig. 1. Chart of reciprocation of microcube with curved surfaces [9]

With a decrease in the characteristic scale of the relief due to the increased diffraction effect, there is a tendency toward the angular expansion of the reflected beam of light. When creating light reflectors for large distances of observation, this effect is undesirable, but for small distances, it is useful and must be used. Diagram of diffraction on a microrelief is shown in Fig. 2, and Fig. 3 illustrates the typical diffraction pattern that occurs for reflected light.

Fig. 2, as shown in the previous publication [9], depicts a metallized part of the surface 24 with an adhesive layer 20 and a portion of the micro relief surface 12 isolated by the air gap. A beam of light 26 falling on the forming surface 10 at an angle φ_0 is partially reflected from the metal layer 24 and after three reflections from three surfaces and a 180° rotation extends from the surface 10 parallel to the direction of the incident beam 26. Due to the diffraction effect, six circular zones of the symmetrical reflector reversal diagram are formed, which are similar to those shown in Fig. 3a.

Thus, part of the rays 28 undergo complete internal reflection from the three surfaces of the interface between the media of the reflector-air and goes in the opposite direction.

Part of the beam 30 does not reflect but passes inside the material element. Rays 32, falling on a microrelief at an angle that is more than a certain critical value, undergo only two reflections from mutually perpendicular surfaces. In this case, they do not fall on the third facet, and leave the element without a "retro-reflective" reflection [10]; thus, they consider the effective reflective surface $S_e(\varphi_0)$.

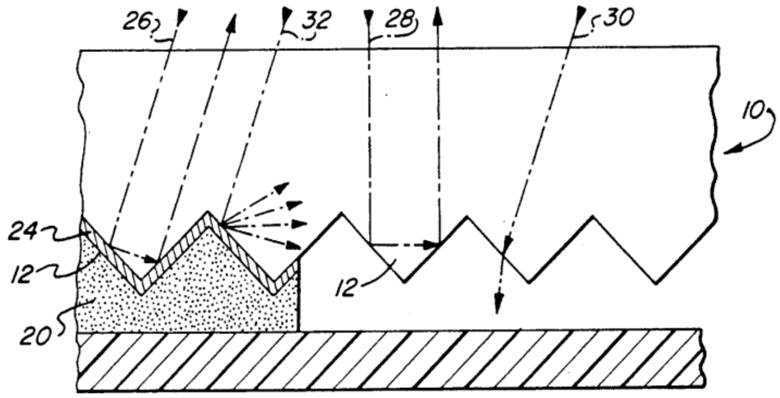


Fig. 2. Diagram of diffraction [9] on the microrelief

The magnitude of the zone of the first diffraction maximum is determined by the known formula [7]:

$$D=1.2\ (\lambda/d), \tag{1}$$

where λ - is the wavelength of light, and the value d - is the diameter of the aperture of the light source, which in this case can be identified with the characteristic size of the microrelief W.

Thus, changing the value of W, one can change the spatial reversal diagram. The effect of diffraction on a surface with a microrelief in step W=152 microns is illustrated Fig. 3b. The center of the structure is denoted by 32, and the circle with the number 34 corresponds to the light cone with the corporal angle Ω=0,5°.

The main energy of the reflected beam is concentrated in the central portion 36, which corresponds to the zero diffraction order, and in the six equidistant districts 38 of the first order of diffraction. Between them there are zones with a lower intensity of reflected beam of light. According to the author [9], such a distribution is not optimal owing to the large spatial heterogeneity of the reflected beam.

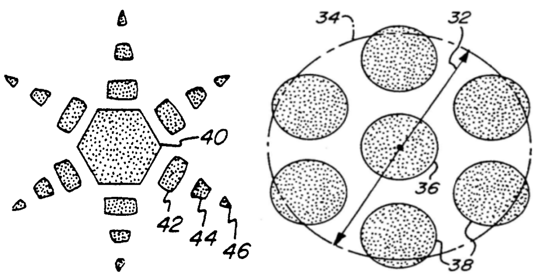


Fig. 3. Diffraction pattern [9] for the light reflected from the microrelief: a) step of relief W=152 microns, b) W=356 microns

However, for an observer, for example, a driver of a vehicle, this is not very significant. The main thing is that in the monitoring cone of 0.5° the bright reflective surface will be clearly observed. In addition, mechanical defects on the actually formed faces of the reflector will lead to blurring in all the viewing angles of the calculated energy diagrams, as shown in Fig. 3. The author [9] also proposes to use the slope of the axes of the associated microcubes to expand the given angular radius of reflection. In this case, you can extend the diagram along one of the axes.

3.2. Determination of requirements to geometric parameters of microprism retro-reflective structures

The basis for any microprismal light-reflective system is a cubic reflector, which consists of three flat mirrors with a right angle at the vertex that intersect at the common point. The general notion of such a generating unit microcube, as the basis for the formation of a retro-reflector, existed for a long time. However, technical solutions for the implementation of such a theoretical proposal arose only in the 30's of the last century. The main problem is the accuracy of making microcubes. It is clear that even small angular deviations in the position of one of these three mirror surfaces result in a significant deviation of the reflected light from the direction of the incident light flux. As a result, the intensity of reflection of the light flux from the surface of the microcube is noticeably reduced.

The first models of light reflectors were created on the principle of multiplication of a traditional single-angle reflector, which is known to have the form of a correct tetrahedron with an angle at the vertex θ_B=90º. Therefore, it was logical for the inventors to simulate the form of a tetrahedron with a single solid-state indenter of the same shape, the size of which should be not very large - 2.0-3.0 mm and then many times in one way or another replicate its shape on a flat forming surface, creating groups of triangular angular reflectors.

For the first time practically feasible process of precise creation of a microprism surface using pin indenters was proposed in a previous work [11]. Furthermore, this technology has been continuously refined to obtain the necessary retro-reflex characteristics for end products. The main efforts were made to increase the efficiency of the retro reflectors by optimizing the optical characteristics and quality of the working surfaces, creating reflectors with an expanded reverse imprint diagram by tilting the axis of the pin indenters to form a relief surface or to change the angles between the mirror faces of the microcubes.

The technology of forming the microcube relief through a solid-state sensor system was practically completed in the work [12]. The author considered numerous variants of constructs of indents with a single microcube at the end, whose axis can be inclined to the indenter's axis at a certain angle to obtain reflectors with the necessary properties. Ways were also proposed for obtaining dies of indentors by connecting a plurality of identical single indents to obtain matrices of required sizes. Systems of replication of a microrelief on flat surfaces with the help of such matrices are also considered. An example of modern indenter technology is a design that is relatively recently patented by “Avery Dennison Corporation” (USA). The method of formation of a microrelief on a flat forming surface with the help of a system of plate indenters is proposed, the necessary form of which can be created by the method of diamond cutting [8], Fig. 4. Plates with the necessary relief then consist of corresponding displacements for the formation of groups of reflectors.

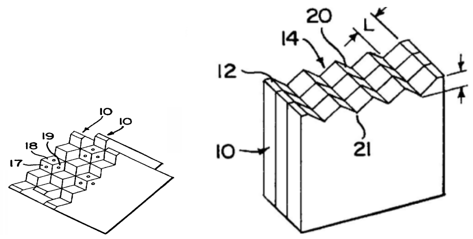


Fig. 4. Reflector [12]: 10, 12 - forming surfaces; 17, 18, 19 - reflective faces

Indents in the form of a finished microrelief structure of relatively small area, made by the method of diamond cutting [8], can later be used to form a microreliefon a surface much larger area [13]. We will call the last multiplication process, in contrast to the above-mentioned replication method by a single indenter or a relatively small indenter matrix.

In the multiplication method, a fragment of the future retro-reflective structure is made, for example, in the form of a regular hexagon with a side L, and later used to form a series of replicas of the microrelief on the plastic surface with a minimum gap ΔL between individual fragments. The scheme of obtaining a microrelief is shown in Fig. 5. Previously, the method of replicating the relief was very popular, as other technologies for the formation of a complex microrelief were practically not available. Note that in some cases it is simply impossible to form the optimally designed microrelief structure, which is developed theoretically, without the use of indenter technology.

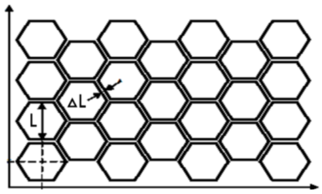


Fig. 5. Scheme of relief formation by multiplication method

An alternative technique is the method of direct mechanical processing of a flat forming surface using solid-state cutters. The method is widely used today for the direct formation of microrelief structures on flat hard surfaces and the creation of matrix-originals of light reflectors. For various reasons, the technology with the use of an indenter or a system of indents does not allow the production of high-quality reflectors. Therefore, today, at the Institute of Information Registration Problems of the National Academy of Sciences of Ukraine (IIRP NAS), technology [14] for the formation of a microcube structure on a flat, one-level forming surface was adopted by the method of mechanical cutting [8] using a diamond cutting tool.

An example of a microrelief [10] of the reflector of the IIRP NAS of Ukraine, which is formed by the diamond cutting method, is given in Fig. 6, which illustrates the galvanic matrix of a symmetric element with a microrelief step W=150 μm.

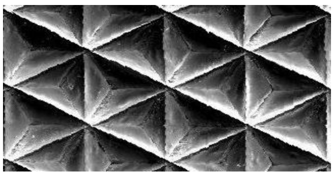
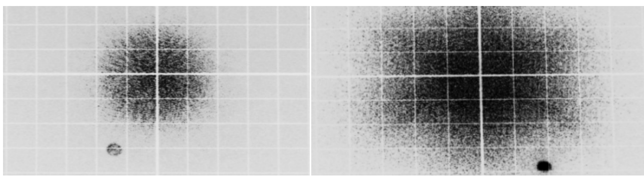


Fig. 6. An example of a microrelief [10] of a symmetrical retro-reflective element of the IIRP NAS of Ukraine

We note that diffraction phenomena can be significant for the formation of the structure of the beam of light, because of this there is an expansion of the reflected beam. Therefore, for light reflectors designed for large distances L_H=1000-2000 m, typical steps of relief W should be at least 1000-1500 μm. Diagrams of the distribution of the intensity of the reflected light flux for some symmetrical microprismal light reflectors of the IIRP NAS of Ukraine with different steps of the microrelief, which illustrate the role of diffraction, are shown in Fig. 7.

The scale in the diagrams is 17 minutes per minute on the retina cell, that is, rice. Fig. 7 illustrates a light reflector for small distances with an angle of expansion of the reflected beam of about 2.5°, and a structure for large distances of observation, illustrated by Fig. 7b, has a reflection angle of 1.2º.



a b

Fig. 7. The diagram of the distribution of the intensity of the reflected light flux of some symmetrical light reflectors of the IIRP NAS of Ukraine: a) is the matrix *SC042 (W*=600 μm); b) - *SK061 (W*=2000 μm)

Thus, the technology of direct mechanical cutting of the microrelief on the forming surface with the help of solid-state cutters allows obtaining reflectors of higher optical quality than the technique of replication of the microcubic structure using pin indenters or a system of indents. When constructing reflectors of various applications, in particular, for different distances of observation, it is necessary to take into account the role of diffraction in the formation of the angular energy diagram of reflected light.

4. DEVELOPMENT OF CONSTRUCTION OF CIRCULAR RETRO-REFLECTIVE ELEMENTS

Developed as a result of this work, the circular retro-reflective element (Fig. 8) is a prefabricated structure consisting of a housing of a retro-reflective element (1) and eight retro-reflective microprismal elements (2), which by means of ultrasonic welding are reliably and hermetically connected to the housing.

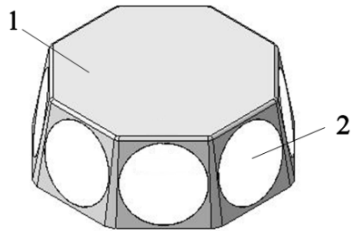


Fig. 8. Circular retro-reflective element: 1- body of the retro-reflective element; 2 - a retro-reflective microprismal element

The body of the circular retro-reflective element (Fig. 9) is a cut octagonal pyramid with a height of 26 mm with an inclination angle of 10°, the base of which is inscribed in a circle with a diameter of 81,4 mm.

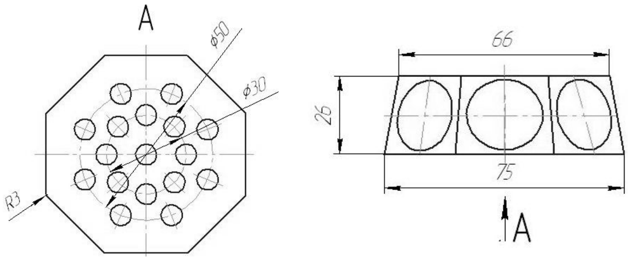


Fig. 9. Body of the retro-reflective element

The basis of the pyramid (A) is a series of deaf holes to provide a reliable fixing of the circular retro-reflective element on the surface of the curtain by the method of gluing. On each of the eight faces, a 24-mm diameter hole is made for the purpose of installing retro-reflective microprism elements. In order that between the vertices of microprism of the retro-reflector microprismal element and the surface of the body of the retro-reflective element is the air layer, the hollow is executed stepwise.

The body of the reflector is made of polycarbonate; the choice of this structural material is due to the need to provide high mechanical strength photodetector. The case is made by injection technology, but any other method can be used, for example, mechanical processing of the corresponding blanks. Reflector inserts are made of sheet polycarbonate with a thickness of 2.0 mm. The microrelief retro-reflective structure on their surface is created by the method of thermal pressing. The insert is placed in a special ring groove depth of 2 mm, which is formed on each of the eight flat forming surfaces.

The reverse side of the element has a series of special holes with a diameter of 8 mm and a depth of 5-15 mm for placing the glue to improve the adhesion of the body of the element with the road cloth.

4.1. Calculation of the parameters of the resonant system of ultrasonic welding of circular light-retrocellular elements and the development of system elements

For welding of circular elements, an ultrasonic welding device (UWD) is used, implemented on the basis of the BRANSON 901aes installation, which is modified to use a piezoelectric converter of ultrasonic oscillations in the resonant system. UWD has been supplemented by a special device that supplies the energy of ultrasound influence to control energy. Since the transverse dimensions of the light reflector body are comparable to the wavelength of the ultrasound in polycarbonate, it must, in fact, be considered as part of the resonant system UWD.

However, due to the higher absorption of ultrasound in polycarbonate compared with the metal sonotrod and a relatively small fraction of the energy of the ultrasonic wave penetrating into the body (approximately equal to the cross-sectional area of the annular tip of the sonotrod to its cross-sectional area), the contribution of the oscillations of the body to the formation of the standing wave is negligible. As a result, when calculating and adjusting the resonance of UWD ultrasonic welding device, only the active part of the resonance system from the generator, the converter, the booster and the sonotrod can be taken into account, considering the tip of the sonotrod free.

The calculation of the elements of the resonant system UWD is based on the approximation of the oscillations of the rods. As known, sound waves are longitudinal, so only longitudinal elastic variations of the rods are considered for calculation. The amplitude of oscillations is determined from the Helmholtz equation for displacements along the axis of the rod:

$$u'' + \left(\ln S\right)' u' + \left(\omega/c\right)^2 u = 0, \tag{2}$$

where S - the length of the length of the cross-sectional area of the rod, $\omega = 2\pi f$ - the circular frequency of oscillations, and c - the speed of sound. The solution of equation (2 has the following form:

$$u = \frac{1}{\sqrt{S}} F, \tag{3}$$

where F -the equation is derived from the canonical form:

$$F'' + \left(\frac{2\pi}{\lambda}\right)^2 \left\{1 - \left(\frac{\lambda}{4\pi}\right)^2 \left[2\left(\ln S\right)'' + \left(\ln S\right)'^2\right]\right\} F = 0, \tag{4}$$

where λ - is the wavelength of the ultrasound in the material of the rod. In accordance with the oscillatory theorem, the equation describes the oscillation of the rod, if the expression in the curly brackets is strictly positive over the entire length of the rod, that is, provided:

$$\lambda \frac{\sqrt{2S''S - S'^2}}{2S} = \lambda \sqrt{\frac{R''}{R}} \le 2\pi . \tag{5}$$

For cylindrical and cone-like sonotrodes, which form straight lines, this condition is adhered to automatically.

In the case of folding rods of constant intersection, the amplitude of oscillation changes inversely proportional to the change in diameters. Oscillations have a resonance if the total length of the rods is multiples of half the wavelength of the ultrasound for one material or if the sum of the form:

$$2\sum_{i}^{n} \frac{l_i}{\lambda_i} = N \tag{6}$$

is equal to the whole number in the case of different materials of constituent parts of the rod. Condition (6) allows us to calculate the lengths of all elements of the active part of the resonant system of the UWD.

The use of the method for adjusting the active elements of the UWD resonant system, based on the recording of amplitude-frequency characteristics, is chosen based on the fact that the approximate model is based on the calculations and also due to the spread of values of the modulus of elasticity of materials of different manufacturers, which depend on the availability of different impurities, degrees of hardening or annealing. When designing the system, all lengths of the UWD elements are increased by about 5%. In view of the maximum simplicity of production and sufficient efficiency, a simple stepped cylindrical form of a sonotrode is adopted. As a material, an aluminum alloy was used, for which the speed of sound in thin rods according to the reference data lies in the range:

$$c = \sqrt{E/\rho} = 5100...5200 \text{ m/c}.$$

Accordingly, the wavelength of the longitudinal oscillations in the sonotrode will be as follows:

$$\lambda = 255...260 \,\text{mm}.$$

In accordance with the adopted method, choose the length of the sonotrode:

$$L = 129 + 7 = 136 \text{ mm}.$$

After adjustment of the length of the sonotrode on the laboratory equipment at the final welding frequency f=19.9 Hz, the length of the sonotrode was L=132 mm.

Another important factor in the application of ultrasonic welding of optical elements is the problem of the dosage of the energy of the influence of ultrasound. Optical plastic materials (polymethyl methacrylate, polycarbonate, and polystyrene) are very rigid materials and well conduct an ultrasound.

This leads to the fact that the energy of the elastic vibrations excited by the hollow sonotrodein the region of the weld is redistributed throughout the volume of the reciprocal element due to the excitation of the Lambda waves propagating in a plane perpendicular to the axis of the sonotrode.

As a result, the interference peak of the amplitude of oscillation in the presence of axial symmetry falls on the central region of the retro-reflective element. Calculations are carried out on the basis of an approximate solution of wave equations for longitudinal and transverse oscillations into which the original vector wave equation is disintegrating in the presence of axial symmetry:

$$\nabla^2\theta = c_l^{-2}\ddot{\theta} \text{ i } \nabla^2\Omega - r^{-2}\Omega = c_t^{-2}\ddot{\Omega}, \tag{7}$$

calculations show that the magnitude of the central maximum of the amplitude of oscillations can be 4-5 times greater than the amplitude of oscillations in the weld region. The undesirable consequences of such a redistribution of oscillation energy are microstructure disturbances (and even possible destruction), mainly in the central region of the retro-reflective element.

To adjust the distribution of absorption of oscillation energy by creating a local concentration of internal stresses in the region of contact of the reciprocal element with the housing, it is proposed to form a protruding acute ring-shaped element that enhances the absorption of elastic waves in this region. Comparison of the results of the welding of retro-reflective elements on a flat platform and on a platform with a protruding ring-shaped element showed the effectiveness of its use, as in the latter version provided reliability and tightness of the connection.

When conducting the test welding and determining the parameters of the operating modes, the signals were monitored at the input and output of the metering device with the help of the digital two-channel oscilloscope Hantek DSO0100627. The comparison of the duration of pulses of welding, measured on oscillograms, with the indications of the digital registrar did not reveal deviations of duration by more than 1%.

4.2. Registration of the diffraction pattern of the reflection of the studied elements

To register light reflected from the surface of the reflector, a special stand CPC-1is used. The stand allows you to record a diffraction pattern that occurs when a light reflector is lit by a laser. An analysis of this picture allows us to draw conclusions about the quality of the retro-reflective surface. The principle of operation of the stand for registration of the distribution reflected from the microrelief of laser radiation CPC-1is based on the registration of a diffraction pattern reflected from the light-reflective element of a narrow beam of light from a "green" laser with a wavelength λ=0,532 microns. The scheme of the stand CPC-1.

The shape and dimensions of the obtained diffraction pattern are compared with the calculated characteristics for this light-retro-element and also compared with the size and shape of the diffraction pattern for the reference retro-reflective element. The data thus obtained allows us to assess the quality of the created retro-reflective element. For example, Fig. 10 shows a typical retro-reflection pattern for a symmetrical light reflector with a microrelief step W=150 μm.

For the same symmetrical retro-reflective element, the diffraction characteristics for one of the three directions of the microrelief in step W=150 μm for the distance to the screen L=2 m are shown in Fig. 11.

These data indicate that when a beam of light with a zero angular resolution falls on the relief, a picture of 6 interference bands will be displayed on the screen. The length of each strip is about 40 mm on both sides of the center for the screen, which is located at a distance of L=2.0 m from the element, that is, the angle difference with respect to the center of the picture is 58.4 angular minutes.

For the non-ideal microrelief, for which there is a deflection of the angle of the reflectors from 90°, there will be an additional blur of the interference pattern in the direction from the center, which must be taken into account when analyzing the quality of the surfaces. This case is depicted by Fig. 12, which presents experimental data for an element with a relief step *W*=600 μm for the observed observation conditions.

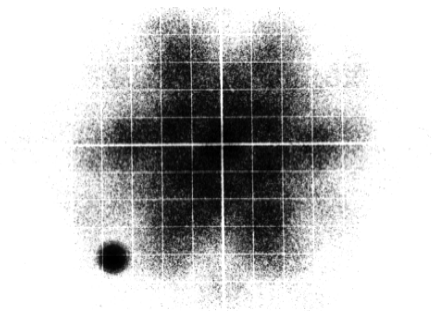


Fig. 10. A typical reversal pattern for a symmetrical retro-reflective element with a step W = 150 μm for *L*=2m. The size of a grid 1cm x 1cm

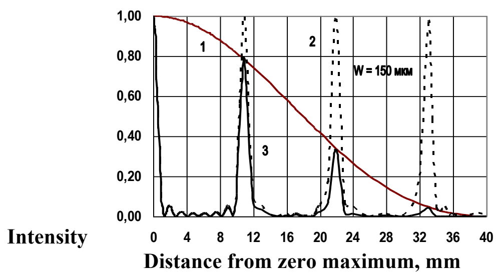


Fig. 11. Diffraction effects for the symmetrical retro-reflective element for the observation distance *L*=2.0 m: cutting step *W*=150 μm, number of cracks *N*=4: 1- diffraction pattern from one slit; 2 - Interference for *N* slits; 3 - integral picture

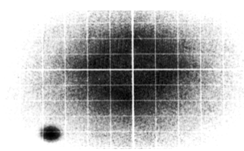


Fig. 12. Reflection for a symmetrical retro-reflective element with a relief step *W*=600 μm for the observation distance *L*=2.0 m. The size of the scale grid is 1 cm x 1 cm

It is easy to see that the structure of the reflected beam of a laser is much larger than the estimated one; the picture does not reveal a noticeable diffraction structure. This indicates the presence of defects in the optical surfaces of this light reflector, which leads to additional isotropic scattering of reflected light. Thus, the comparison of the experimentally obtained distribution of the intensity of the laser beam after its reflection from the reciprocal surface with the calculated data in relation to the placement of interference maxima and their number makes it possible to estimate the quality of the optical surfaces with the microrelief. According to the technical specification, 500 prototypes were produced, which were transferred to the partner organization - Kyivavtodor municipal corporation for installation and experimental exploitation. In October 2017, installation of prototype samples was carried out on the streets of Kyiv; sample supervision continues (Fig. 13) [15, 16].

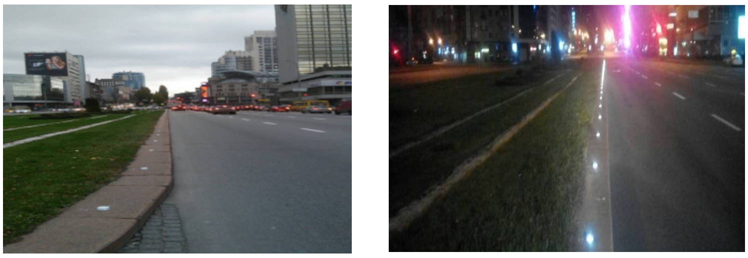


Fig. 13. Experimental implementation of retro-reflective elements

5. CONCLUSIONS

1. The scheme of the technological route for the production of circular curtain reflectors is developed, which includes a series of successive and parallel technological operations for the production of individual elements of light reflectors.
   The design of a circular curb curtain with eight retro-reflective elements is developed, which is a cut octagonal pyramid with a height of 26 mm, the basis of which is inscribed in a circle with a diameter of 81.4 mm. In each facet of the pyramid, a highly effective microprism retro-reflective element is mounted, which provides a reliable visualization of the steep rounds of the road and obstacles in the dark during the day. The design of the housing of the retro-reflector element ensures its reliable mounting by the method of adhesive bonding.
2. A technological complex for the production of circular retro-reflective elements was created and implemented at the pilot-experimental section at the Institute of Information Registration Problems of the National Academy of Sciences of Ukraine, which ensures the manufacture of retro-reflective elements with stable geometric parameters; the method used is the method of injection molding on precision thermoplastics machines. Micropriceretro-reflective elements were manufactured with a reciprocity factor of 650-700 c/(lux m^2), which exceeds the requirements of DSTU 4036-2001; the circular elements were manufactured by the method of ultrasonic welding, which provides reliable and tight fastening of the retro-reflective element in the case.
3. For the manufacture of microprocessor light reflectors, an appropriate mold was created for use in pressure injection molding machines.
4. Autonomous testing of manufactured elements has been carried out. The results of autonomous tests give grounds to assert that circular retro-reflective elements will maintain efficiency (light-reflection effect) after exposure to atmospheric precipitation elevated to +60° C and lowered to -20°C.

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