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MODELING AND CALCULATION OF THE CONTROL UNIT FOR THE FOCUS POSITION AT LASER-FIELD WELDING

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ABSTRACT

Ensuring the quality of laser-field welding requires monitoring not only the energy parameters of radiation and the intensity of the electrostatic field, but also the position of the focal spot. The calculation of the control channel for the laser radiation focus position during welding, which determines the parameters of the welded seam quality, is performed in the work. The active optoelectronic system parameters for the adjustment subsystem of the focus position relative to the seam with laser illumination of the seam are calculated, the model of the control channel is suggested taking into account the thermophysical phenomena occurring in the welding zone.

Keywords: laser welding, laser-field technology, focus, laser.

1. INTRODUCTION

Stabilization of energy parameters in the interaction zone of laser radiation with a metal and an increase the accuracy of laser radiation spot positioning relative to the welded seam are the optimal methods for constructing automatic control systems for hybrid laser technological complexes, which leads to stabilization of the technological process quality indicators.

Accuracy of the specified parameters reproduction of the tool mechanical movements, laser head, along a complex trajectory in three-dimensional space, is one of the factors to which modern methods of metalworking, the precision products production of complex configuration, welding operations and assembly processes, are constantly increasing demands. The trajectory tracking of motion with high accuracy is provided by non-contact methods, in particular, based on measuring both the light flux of the metal thermal radiation and reflected from the connected surfaces [2]. The problem of monitoring the focus position of laser radiation can be solved with the help of a photodetector line-array.

2. THE ENERGY BALANCE EQUATION

The process of laser radiation interaction with a metal can be described by the energy balance equation [6]:

$$W_{LR} + W_{FP} + W_{LP} = W_{EM} + W_{MV} + W_R + W_{KE}. \tag{1}$$

Where: W_{LR} - energy of laser radiation supplied to the treatment zone; W_{FP} - shielding gas pressure; W_{LP} - impact of a laser radiation mechanical energy on a metal surface; W_{EM} - energy spent on melting of metal and its evaporation; W_{MV} - mechanical vibrations in the metal; W_R - reflected energy from the laser radiation interaction zone with a metal; W_{KE} - energy expended for the emission of molten metal particles.

Energy input: W_{LR}; $W_{FP} = \frac{m_I v_I^2}{2}$, where

m_I - protective gas mass flow, v_I - protective gas flow rate; W_{LP}.

Energy expended [1]: $W_{EM} = c\gamma(T)\frac{\partial T}{\partial t} + div\overline{W}$,

where $c\gamma$ - volumetric heat capacity; T – temperature; t - time; $\overline{W}$ - heat flow, $\overline{W} = -\lambda_T(T)\overline{gradT}$;

λ_T - coefficient of thermal conductivity; W_R - reflected energy (is about 30% of the laser radiation power, since the metal temperature exceeds the melting point and the absorption coefficient is 0.7); $W_{MV} = h\nu_p$ - energy expended on excitation of mechanical vibrations in a metal (is 5-6% of the laser radiation power); $W_{KE} = \frac{m_O v_O^2}{2}$, where m_O - mass flow of molten metal emitted particles; v_O - the velocity of molten metal emitted particles.

3. PARAMETERS OF A MOVING HEATING SOURCE - LASER RADIATION

The solution of the optimization problem includes the stage of exposition the law of changing the technological parameters of a hybrid laser technological complex as a function of time. To solve this problem, we give the required distributed control Q(x,t), defined for $t \geq t_0$ in a certain region Ω of space R^n. Let the restrictions that the control parameters must satisfy be known u(t), s(t), k(t), eg.:

$$\begin{aligned} &P_{\min} \leq u(t) \leq P_{\max}, \\ &0 \leq s'(t) \leq V_{\max}, \\ &D_{\min} \leq k(t) \leq D_{\max}. \end{aligned}, \tag{2}$$

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$$P'_{\min} \le u'(t) \le P'_{\max},$$
$$0 \le s''(t) \le V'_{\max}, \qquad (3)$$
$$D'_{\min} \le k'(t) \le D'_{\max}.$$

{ }{ }

Here the system (2) represents the restrictions on the power, speed and size of the source. System (3) describes the limitations on the change rate of the above technological parameters of a hybrid technological complex [3, 5].

It is necessary to find parameters u(t), s(t), k(t) for which equality

$$Q(x, t) = F(x, t) \qquad (4)$$

holds for any $x \le D$, $t_0 \le t \le t_m$.

If the shape of the mobile source has an arbitrary form and coincides with the form of the given distributed control Q(x, t), the problem (4) can be solved by defining the parameters u(t), s(t) as follows:

$$u(t) = \int_D F(x,t)dx,$$
$$s(t) = \frac{1}{u(t)} \int_D x \cdot F(x,t)dx, \qquad (5)$$

$$F(x, t) = u(t)\, \psi\, [x - s(t), k(t)], \qquad (6)$$

where x, t - spatial and temporal coordinates; u(t), ψ(x, k), s(t) - functions describing the intensity, shape and coordinates of the laser radiation impact center, respectively; k(t) - coefficient of concentration, determining the degree of effect concentration.

The function s(t) is usually called the law of motion of the source.

For the case of the sources shape of a given form (uniform, Gaussian distribution by a spot), it is expedient to consider the corresponding variational formulation of problem (4) for numerical solution and to present it as follows [7]:

$$J_i = \left[Q_{\sum i}(x) - F_{\sum i}(x)\right]^2 \to \min \qquad (7)$$

where:

$$F_{\sum i}(x) = \frac{1}{\Delta t_i} \int_{t_{i-1}}^{t_i} u(t)\psi(t + s(t), k(t)]dx,$$

$$Q_{\sum i}(x) = \frac{1}{\Delta t_i} \int_{t_{i-1}}^{t_i} Q(x,t)dt,$$

$\Delta t_i = t_i - t_{i-1}$ - Lengths of intervals on which the time axis is broken.

The task here is to ensure the equality of the substance's inputs over the time Δt_i from the given impact Q(x, t) and the movable source F(x, t) in any arbitrarily small subdomain of the domain D of the control object. The states of the object under the action of a distributed and movable source on it will be close for sufficiently small intervals Δt_i.

For the case of given specific values of the laser radiation power density and the velocity of the laser beam, we take the average values of the microhardness in depth, determined by the experimental data.

Experiments were carried out with laser power densities of $2 \cdot 10^6$ and $8 \cdot 10^6$ $\frac{W}{m^2}$, the laser beam speed along the surface was 560 and 1120 $\frac{mm}{min}$, the electrostatic field intensity was 1.03 $\frac{MV}{m}$ [4]. The obtained microhardness distributions along the depth of the machined part were approximated by power law dependence with the following results:

a) for $q_r = 2 \cdot 10^6\ \frac{W}{m^2}$, $v = 1120\ \frac{mm}{min}$, $E = 1.03\ \frac{MV}{m}$ (Figure-1).

$HV_{50}(h) = -336612h^3 + 58119h^2 - 2792{,}9h + 1002{,}8.$

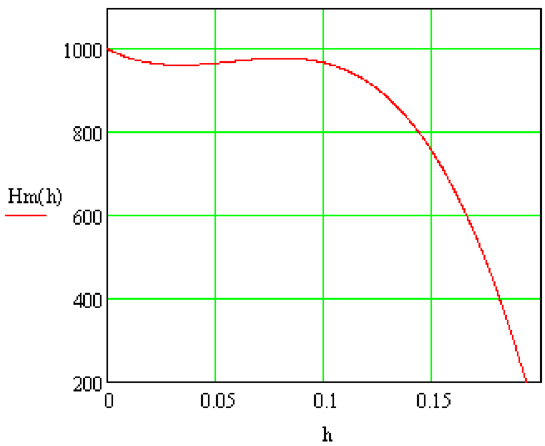

Figure-1. Microhardness of samples in depth.
($q_r = 2 \cdot 10^6\ \frac{W}{m^2}$, $v = 1120\ \frac{mm}{min}$, $E = 1.03\ \frac{MV}{m}$).

b) for $q_r = 8 \cdot 10^6\ \frac{W}{m^2}$, $v = 1120\ \frac{mm}{min}$, $E = 1.03\ \frac{MV}{m}$ (Figure-2).

$HV_{50}(h) = -46914h^3 + 14116h^2 – 2375{,}8h + 1054{,}8.$

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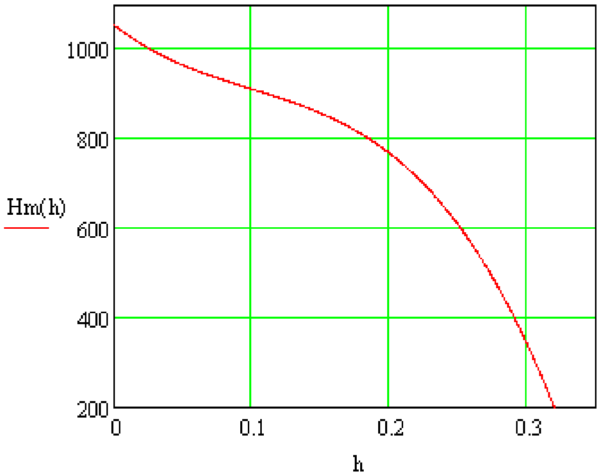

Figure-2. Microhardness of samples in depth.
($q_r = 8 \cdot 10^6 \dfrac{W}{m^2}$, $v = 1120 \dfrac{mm}{min}$, $E = 1.03 \dfrac{MV}{m}$).

c) for $q_r = 2 \cdot 10^6 \dfrac{W}{m^2}$, $v = 560 \dfrac{mm}{min}$, $E = 1.03 \dfrac{MV}{m}$ (Figure-3).
$HV_{50}(h) = -26753h^3 + 11319h^2 - 1361{,}6h + 1219$.
d) for $q_r = 8 \cdot 10^6 \dfrac{W}{m^2}$, $v = 560 \dfrac{mm}{min}$, $E = 1.03 \dfrac{MV}{m}$ (figure. 4).
$HV_{50}(h) = -68485h^3 + 25169h^2 - 2288{,}1h + 1217$.

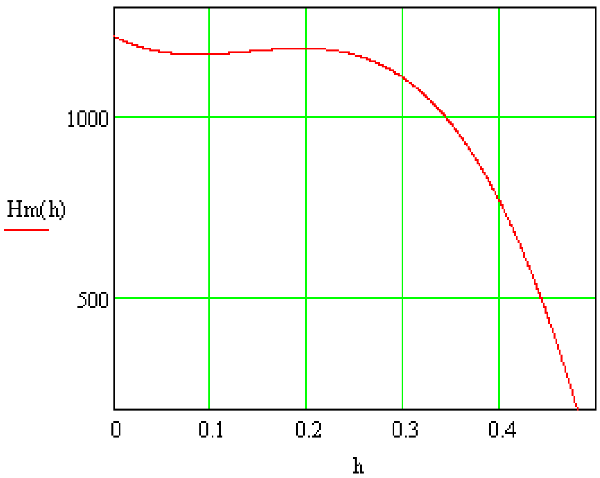

Figure-3. Microhardness of samples in depth
($q_r = 2 \cdot 10^6 \dfrac{W}{m^2}$, $v = 560 \dfrac{mm}{min}$, $E = 1.03 \dfrac{MV}{m}$).

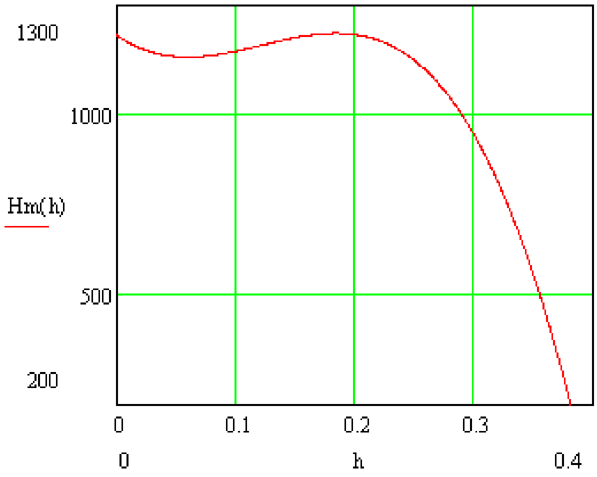

Figure-4. Microhardness of samples in depth.
($q_r = 8 \cdot 10^6 \dfrac{W}{m^2}$, $v = 560 \dfrac{mm}{min}$, $E = 1.03 \dfrac{MV}{m}$).

4. LASER ILLUMINATION CHANNEL CALCULATION

A 10 mm illumination zone at a distance of 150 mm from the objective (Figure-5) is formed in the laser illumination channel by radiation from a semiconductor laser λ = 0.84 μm with an angle of divergence of the laser beam of 40 deg. The distance from the front focus to the first surface of the lens is 22.3 mm. The calculated wavelength is 0.84 μm. The focal length is 25.1 mm.

In the laser illumination channel, the illumination area is relatively large and since it is not required such a high quality as in optical imaging systems, the objective is made from a single lens [6].

To ensure a small convergence of the laser beam at the output of the objective, the emitting surface of the laser is located at a distance of 0.5-1 mm from the point of the lens foreground. The focal length and the diameter of the lens are selected from the condition of providing the most appropriate mutual arrangement of the laser and the lens, and also taking into account the laser emitter linear size (maximum 1 mm) and the laser radiation divergence angle (40grad) (Table-1).

5. PHOTODETECTOR CHANNEL CALCULATION

The choice of the photodetector channel optical parameters requires consideration of such requirements and limitations as:

- linear size of the subject area (weld zone), a qualitative image of which should be formed in the photo-receiver plane - 10 mm;
- aberration cup diameter (not more) - 10 μm;
- the photodetector element image size in the weld plane - 20 μm;
- the number of sensitive elements in the photodetector array (not less than) - 500;
- distance from the lens to the weld - 150 mm;

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- the level of irradiation sufficiency of the photodetector sensitive elements from the laser welded plane of the weld (energy estimate is given below);
- use of a photodetectors line-array of type DALSA with the size of a sensitive element 14x14 microns or 13x13 microns.

The ratio of the photodetector element image size in the weld plane (20 µm) and the photodetector sensor element size (14 µm) allows obtaining the required linear magnification of the objective in the direction from the photodetector P to its image in the welded seam plane. Magnification $M = \frac{20}{14} \approx 1.5^x$.

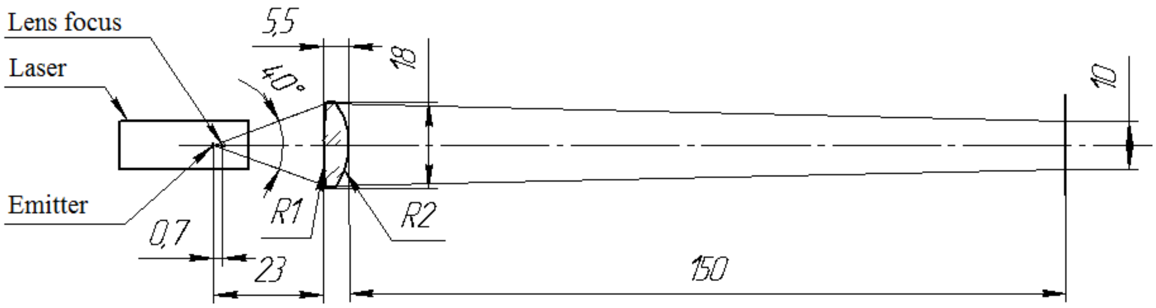

Figure-5. The path of the rays and the design parameters of the laser illumination channel.

Table-1. The lens design parameters.

Designation	Name	Radius R_1, mm	Radius R_2, mm	Thickness d, mm	Material (GOST 3515-94)	Diameter D, mm
-	Lens	51,05	-16,444	5,5	K8	20

The required values of the objective focal length f' and the distance s from the photodetector to the lens in the first approximation are obtained from the geometric optics formulas for a thin lens.

s' = f '+ x' = 150,
M = x'/f' = f/x = s'/s = 1.5.

Where: s' - distance from welded seam to lens; x' - distance from the focus of the lens to the weld; f - focal length; x - distance from the focus of the lens to the photodetector.

From here s = 100 mm, f' = 60 mm.

These requirements for the optical system of the photodetector channel are realized in a three-lens objective. In one - and two-lens objective, these requirements cannot be realized at the same time.
The design parameters of the lens (Figure-6).

The calculated wavelength is 0.84 µm. The focal length is 71.3 mm. The distance from the front focus f to the first surface of the lens is 85.5 mm. The distance from the photodetector to the first surface of the lens is 133 mm. The distance from the last surface of the lens to the back focus f ' is 42.8 mm. The parameters of the lenses and mirror are shown in Table-2.

A flat breaking mirror installed in the space between the photodetector and the lens will reduce the size. With the help of similar mirrors, it is possible to optimize the optical part dimensions of the photodetector channel. Flat mirrors do not affect image quality [8].
Calculation of the lens quality parameters, performed in the "Zemax" program, is shown in Figures 7 and 8.

Figure-7 shows a scatterplot in the weld plane for the points of the view field corresponding to a deviation from the optical axis of 0, 3.8, and 5 mm. The diameter of the scattering circle does not exceed 5 µm. Figure 8 shows the modulation transfer function of the objective for three points in the field of 0, 3.8, 5 mm and for an ideal optical system. The identity of the graphs indicates the ideal, i.e. diffraction limited image quality in the entire field of view with a diameter of 10 mm.

6. ENERGY ASSESSMENT

The energy evaluation will allow showing a sufficient irradiation of the photodetector array sensitive elements with the chosen optics parameters of the laser channel and the photodetector channel.

Initial data for calculation:

- laser radiation power: P_l;
- transmission of the laser channel lens τ_l, no less than: 0.8;
- threshold exposure of the photodetector at λ = 0.84 µm, $H_t = 13 \cdot 10^{-12} \frac{W \cdot s}{cm^2}$;
- the saturation exposure of the

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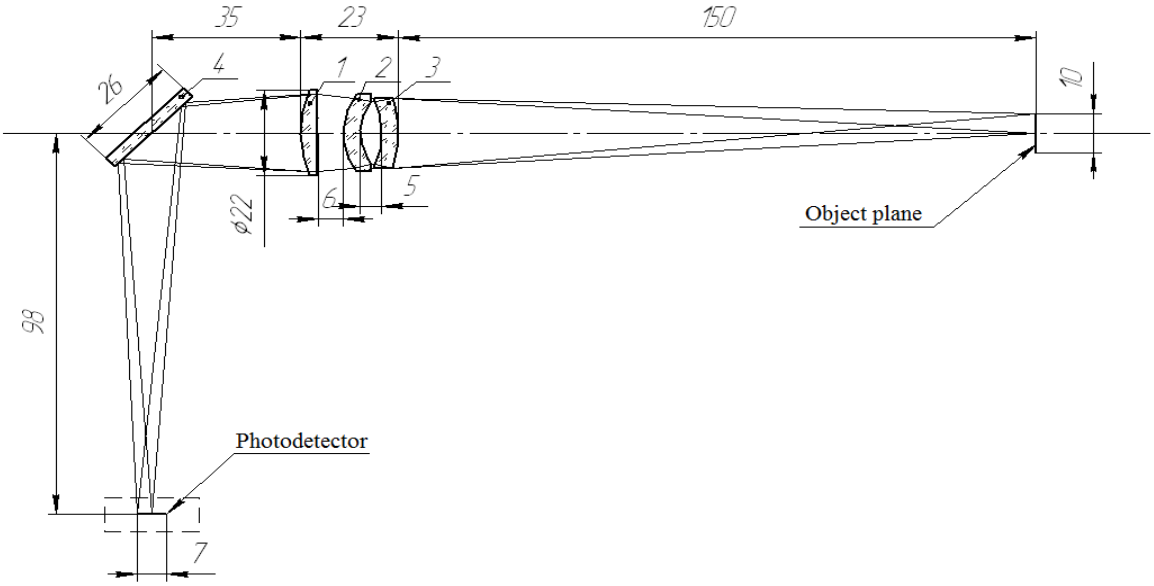

Figure-6. Beam path and design parameters of the photodetector channel. (1, 2, 3 - lens; 4 - mirror).

Table-2. Design parameters of the optical system.

Designation	Name	Radius R_1, mm	Radius R_2, mm	Thickness d, mm	Material (GOST 3515-94)	Diameter D, mm
1	Lens	31,62	-4966	4,0	STK12	22
2	Lens	18,03	13,614	4,0	TF4	20
3	Lens	-21,48	-27,54	4,0	BF25	18
4	Mirror	-	-	-	-	26

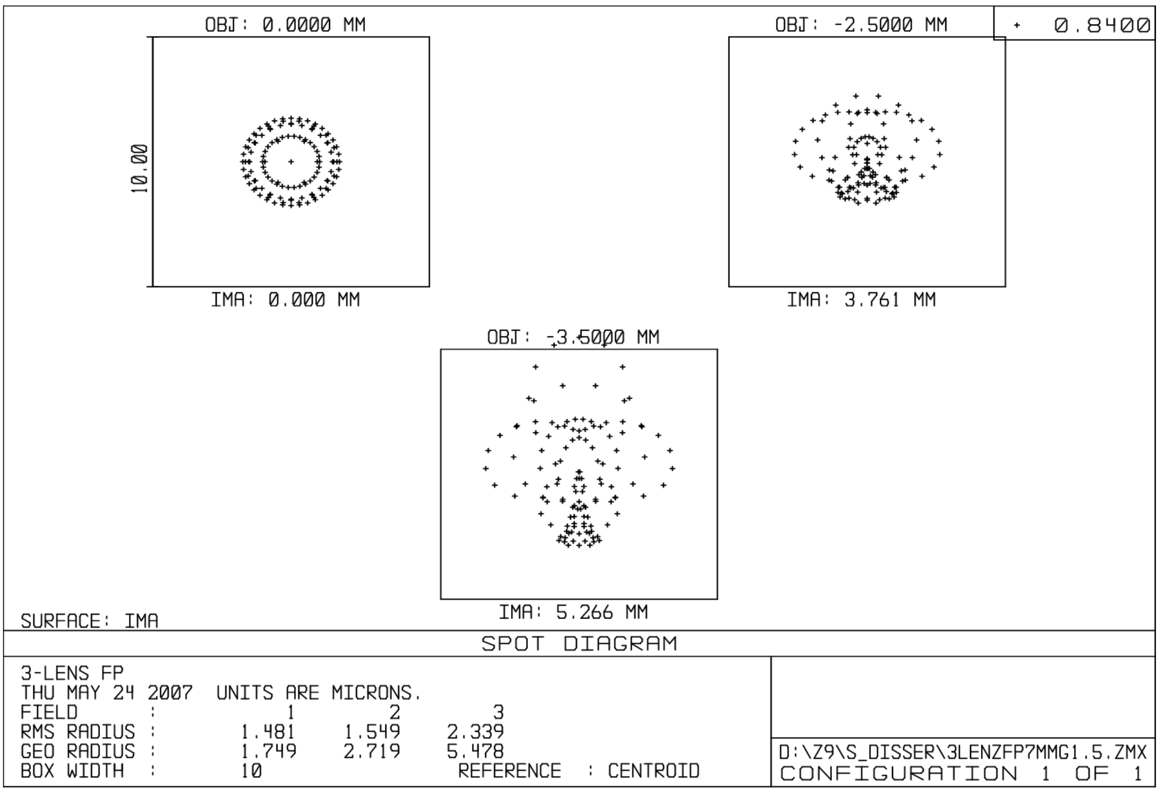

Figure-7. Diagram of the scattering spot in the plane of the welded seam for points of the view field corresponding to a deviation from the optical axis of 0, 3.8, and 5 mm.

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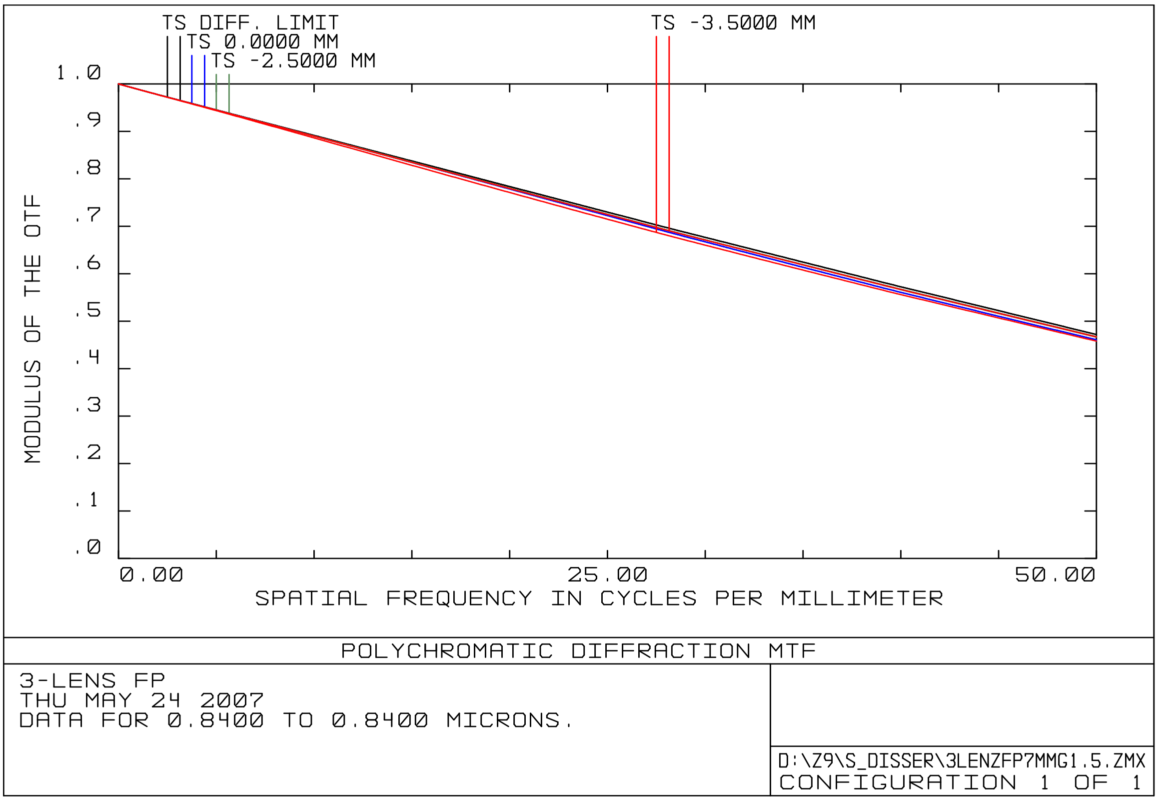

Figure-8. Modulation transfer function of the lens.

photodetector at $\lambda = 0.84$ μm, $H_s = 23\cdot 10^{-9}\ \frac{W\cdot s}{cm^2}$;

- the transmission of the photodetector channel objective taking into account the mirror, $\tau_p = 0.8$;
- coefficient of metal reflection in the weld plane, $\rho = 0.7$;
- area of the laser spot in the weld plane, $S_l = 0.8$ cm^2;
- half of the photodetector channel objective aperture angle, $\alpha = 2.86°$;
- body aperture angle of the photodetector channel lens, $\Omega = 2\cdot \pi \cdot (1-\cos\alpha) = 0.0078$ sr;
- lens linear magnification in the direction from the photodetector to the weld, $M = 1.5^x$.

The calculation is as follows. Energy illumination (irradiance) from the laser in the weld plane:

$$E_w = \frac{P_l \tau_p}{S_l} = \frac{0.2\cdot 0.8}{0.8} = 0.2\frac{W}{cm^2}.$$

Energy brightness of the laser spot:

$$B = \frac{E_w \rho}{\pi} = \frac{0.2\cdot 0.7}{3.14} = 4.45\cdot 10^{-2}\ \frac{W}{cm^2\cdot sr}.$$

Irradiation in the photodetector plane:
$E_p = B\Omega\tau_p M^2 = 4.45\cdot 10^{-2}\cdot 0.0078\cdot 0.8\cdot 1.5^2 =$
$= 0.6\cdot 10^{-3}\ \frac{W}{cm^2}$.

In the case of the standard photodetector charging time t_c = 25 μs, the threshold irradiance of the photodetector is:

$$E_t = \frac{H_t}{t_c} = \frac{13\cdot 10^{-12}}{25\cdot 10^{-6}} = 0.5\cdot 10^{-6}\ \frac{W}{cm^2}.$$

It follows that the signal-to-noise ratio will be:

$$\frac{E_p}{E_t} = \frac{0.6\cdot 10^{-3}}{0.5\cdot 10^{-6}} = 1200.$$

The maximum permissible accumulation time should not exceed:

$$t_{max} = \frac{H_s}{E_p} = \frac{23\cdot 10^{-9}}{0.6\cdot 10^{-3}} = 38\cdot 10^{-6}\ \text{s}.$$

Hence, it can be concluded that the laser illumination energy estimate calculation of the welded seam shows sufficient irradiation of the photodetector array sensitive elements with the chosen parameters of the laser channel optics and the photodetector channel.

7. CONCLUSIONS

The presented method of controlling the laser radiation focus position relative to the welded seam, taking into account its geometry, significantly improves the quality of the welded seam.

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