UDC 621.43.068

THE PROGRAM CYBERDIESEL FOR MATHEMATICAL MODELING OF FUEL SUPPLY AND LOCAL INTRACYLINDER PROCESSES IN A DIESEL ENGINE WITH VOLUMETRIC CARBURETION

V.Yu. Maschenko

Saint-Petersburg state nautical technical university
E-mail: masvladimir@yandex.ru

The program CyberDiesel is developed on the basis of complex mathematical model of fuel supply and local intracylinder processes in a diesel engine with volumetric carburetion. The program is intended for solving practical problems of coordinating constructive and adjusting parameters of fuel equipment and combustion chamber of a diesel engine by mathematical modeling methods.

The analysis of ship energetics development shows that the topicality of the problem of increasing economic and ecological indicators of diesel engines does not decrease. One of the main methods of solving this problem is coordinating constructive parameters of fuel equipment (FE) and combustion chamber (CC) at the stages of development of a new diesel engine and modernization of the existing one. Currently such coordination is carried out, mainly, by expensive development tests. The efficient means of reducing the cost and duration of development tests is application of software directed to solution of special problems at designing FE and CC.

Currently there are not enough software products having a property of direction to design application solution. Known foreign programs (KIVA, Star-CD, FIRE etc.) are expensive and bulky. Computation with a bulk of initial and boundary conditions, which are difficult to be determined, do not always result in valid results. It complicates their use for solving the assigned application. Partially this disadvantage is overcome in known domestic bundled software Diesel-RK, developed in N.E. Bauman's MSTU. Its advantage is handy and intuitively comprehensible interface for user. Inspite of this fact, it should be noted that the «kernel» of bundled software is mathematical model of carburetion and fuel burning in CC proposed by N.F. Razleitsev. This mathematical model is adapted most of all other known models to solving the diesel engine design problems. However, conditionality of division of space, occupied by fuel torch, into areas as well as randomness of assigning these areas boundaries and heat-exchange parameters in them are typical for it. Absence of the model of several required experimental data on these parameters did not allow the author to model rather strictly the processes of carburetion and combustion in diesel engine and describe dependence of their quality on many existing factors. Besides, the quantity of empirical coefficients is rather high. In this connection, the model «adjustment» performed by the experimental curves of heat generation of diesel engine basic variant is rather laborious.

Taking into account the stated above the developers of the program CyberDiesel tended to attach the following properties to the basic mathematical model [1].

1. Possibility of modeling the fuel supply processes and tracing its influence on intracylinder processes.
2. Locality of describing actuating medium parameters in CC. This very property may be the required condition for program operation results to reflect adequately the influence of CC profile change and FE parameters on indicator indices of operational cycle.
3. Confirmability of mathematical modeling adequacy by the results of the experimental investigations. And this property should be referred to the whole model and to separate submodels of a complex of processes fuel supply – carburetion – combustion.

The proposed program is based on the following submodels of elementary processes occurring in FE and CC: fuel supply, fuel jet decay into drops, development of vaporizing fuel jet, mixing fuel vapors with gas, preflame reactions, heat release at combustion and formation of nitric oxide NO. Design factors of fuel equipment and combustion chamber, thermal properties of fuel and air, several empirical coefficients and computational network parameters are maintained as the initial data. The main results of computation are an indicator diagram, characteristics of heat release and NO formation. Characteristic of fuel supply, fields of component and actuating medium rate concentration, fields of temperatures and pressures are derived as intermediate results. In this case, it is significant to note that the results of the program operation with the experiments were juxtaposed not only for design values of indicator diagram and heat release characteristics but also for calculating intermediate processes.

Fuel supply process is designed using known dynamic model. The method of solving the equation system was borrowed from B.P. Pugachev. The experience of experimental-calculated investigations showed that at certain specific initial data the model responses inadequately to the change of pressure tubing (TVD) length: increase of TVD length according to the model results in decrease of pressure pulse lagging in a nozzle relative to a pulse in TNVD. The example of such designed variant for diesel engine ChN30/38 (D42), made for TVD lengths 100 and 600 mm is given in Fig. 1.

It is obvious that this result does not correspond to the facts. The analysis of the expressions showed that the reason of such reaction is in inaccuracy of expressions for fuel rates in delivery pipe boundary sections.

Boundary conditions of the basic technique [2] set the values of fuel motion rate in initial (i=0) and final (i=n) sections of TVD by the following equations:

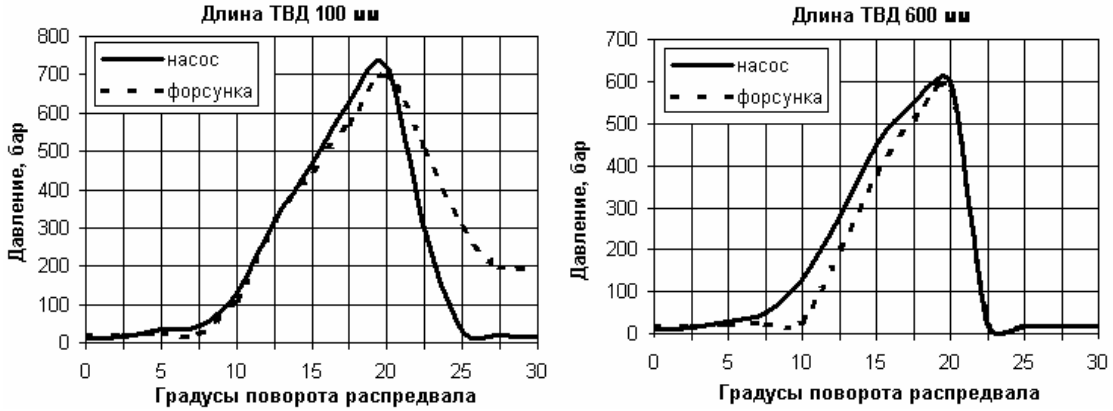

Fig. 1. *Pulses in fuel equipment at basic variant of boundary conditions*

Давление – Pressure; Длина ТВД – TVD length; Насос – Pump; Форсунка – Nozzle; Градусы поворота распредвала – Degrees of camshaft rotation

$$w_{0,j+1} = w_{0,j} + \frac{1}{\rho}\frac{\Delta\tau}{\Delta x}(p_{ш,j+1} - p_{1,j+1}),$$

$$w_{n,j+1} = w_{n,j} - \frac{1}{\rho}\frac{\Delta\tau}{\Delta x}(p_{ф,j+1} - p_{n-1,j+1}), \qquad (1)$$

where Δx and $\Delta\tau$ are the computational grid pitches, respectively, by the coordinate of TVD distance x and time coordinate τ; i,j are the numbers of grid nodes, corresponding to conditions $x=i\Delta x$ (i=0,1,2,...,n) and $\tau=j\Delta\tau$ (j=0,1,...), $w_{i,j}$ is the rate in the node, $p_{i,j}$ is the pressure in the node, $p_{шj+1}$ and $p_{фj+1}$ are the pressures in TNVD connection and nozzle, respectively at the next stage of timing.

The proposed equations of boundary conditions are of the following form:

$$w_{0,j+1} = w_{0,j} + \frac{\Delta\tau}{\rho\Delta x}(p_{ш,j} - p_{1,j}) +$$
$$+\frac{\Delta\tau}{\Delta x}|w_{ш,j}|(w_{ш,j} - w_{1,j}),$$
$$w_{n,j+1} = w_{n,j} - \frac{\Delta\tau}{\rho\Delta x}(p_{ф,j} - p_{n-1,j}) -$$
$$-\frac{\Delta\tau}{\Delta x}|w_{ф,j}|(w_{ф,j} - w_{n-1,j}). \qquad (2)$$

Comparison of expressions shows that (1) is a special case of (2) if the rates in TNVD connection and nozzle are set identically zero $w_{ш,j}\equiv w_{ф,j}\equiv 0$. It is known that in up-to-date high-forced diesel engines the fuel motion rates in TVD may differ significantly from zero. Assumption of zero speed in boundary sections results in considerable underrating of design pressures in TVD (especially in the first section).

Diagrams designed by the adjusted technique (that is applying equations (2) of boundary conditions in TVD) by the initial data of the analyzed design variant are introduced in Fig. 2. It turned by calculations out that increasing TVD length the lag by rotation angle of camshaft (by time) of pressure pulse in nozzle from pressure pulse in TNVD grows (Fig. 2). Besides, pressure maximum in nozzle decreases considerably. The obtained result corresponds to the real process of fuel supply.

Comparison of the design and experimental characteristics of injection pressure depending on camshaft rotation angle obtained for fuel equipment of diesel engine ChN30/38, given in Fig. 3. Deviation of pressure design values from the observation ones does not exceed 120 MPa that corresponds to maximal relative error 10 %.

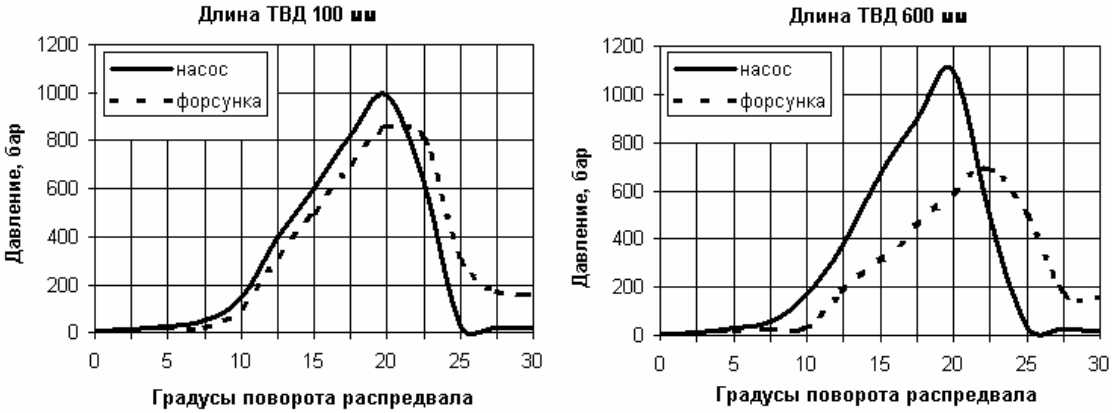

Fig. 2. *Pressure pulses in fuel equipment at adjusted variant of boundary conditions*

Давление – Pressure; Длина ТВД – TVD length; Насос – Pump; Форсунка – Nozzle; Градусы поворота распредвала – Degrees of camshaft rotation

Fig. 3. *Characteristics of injection pressure*

Давление – Pressure; Градусы поворота распредвала – Degrees of camshaft rotation; Эксперимент – Experiment; Расчет – Design

The design of fuel jet development process is formed on the basis of equations describing the complex of processes: drop advance, formation of cocurrent gas flow, interaction of two-phase jet with combustion chamber walls.

Drop advance in CC space is modeled according to Lagrangian method known in classical hydromechanics. For this purpose, continuous injection characteristic is discretized with the design interval by time $\Delta\tau$ so that one calculated portion of fuel with mass m_{fi} escapes from nozzle injector per each interval.

Mass of i portion (index of portion number corresponds to the interval i=1,2,...,n_f) is calculated by an average value of injection characteristic ordinates at the design time lag:

$$m_{f_i} = (\overline{d\sigma / d\tau})_i \frac{G_ц}{2\tau_{впр} i_c} \Delta\tau. \qquad (3)$$

The coordinate of velocity vector on abscissa axis for i portion at the output from nozzle hole:

$$w_{x\,i} = \frac{m_{f_i}}{\rho_f\ (\mu_c f_c)\ \Delta\tau} = (\overline{d\sigma / d\tau})_i \frac{G_ц}{\rho_f\ (\mu_c f_c)\ \tau_{впр}\ i_c}. \qquad (4)$$

In formulas (3) and (4) $(\overline{ds/d\tau})_i$ is the ordinate of relative differential injection characteristic for i portion; $G_ц$ and ρ_f are the injection rate and fuel density, respectively; μ_c and f_c are the discharge coefficient and the area of flow section of nozzle hole, respectively; i_c is the number of nozzle holes in a nozzle; $\tau_{впр}$ is the time of injection.

Projection of velocity vector to the ordinate axis for the i portion at the output from nozzle hole may be calculated by the formula obtained from the theoretical solution of O.N. Lebedev:

$$w_{y\,i} = K_w \sqrt{\frac{\sigma_f}{\rho_f d_{32i}}},$$

where σ_f is the coefficient of fuel surface tension; ρ_f is the fuel density; K_w is the numerical coefficient.

Average Zauter diameter of a drop d_{32i} is constant in the range of i portion and calculated by the known formula of Tanasava:

$$d_{32i} = C_d \sqrt{g} \frac{d_c}{w_i} \left(\frac{\sigma_f}{10\rho_f} \right)^{0,25} \left(1 + 0,331\mu_c f_c \sqrt{\frac{10g}{\sigma_f \rho_f d_c}} \right),$$

where σ_f is the coefficient of fuel surface tension, g=9,81 m/s^2 is the free fall acceleration; d_c is the nozzle hole diameter; C_d is the numerical coefficient; w_i is the velocity vector module for i portion; $w_i^2 = w_{x\,i}^2 + w_{y\,i}^2$.

Resistance to drop motion in viscous medium is calculated using the formula known from classical hydromechanics for flowing around a spherical body. Projections of acceleration vector for i portion:

$$\frac{dw_{к\,x\,i}}{d\tau} = -C_{D\,x} \cdot \frac{\rho_a}{\rho_f} \cdot \frac{(w_{к\,x\,i} - w_{a\,x\,i})^2}{d_{32i}},$$

$$\frac{dw_{к\,y\,i}}{d\tau} = -C_{D\,y} \cdot \frac{\rho_a}{\rho_f} \cdot \frac{(w_{к\,y\,i} - w_{a\,y\,i})^2}{d_{32i}},$$

where C_{Dx} and C_{Dy} are the empirical resistance coefficients to drop motion in directions x and y,respectively; $w_к$ and w_a are the rates of motion of drop and air, respectively.

The design and proper experimental characteristics of fuel jet motion for FE of diesel engine DN23/30 (40D) are given in Fig. 4. It turned out that the difference of the design and experimental magnitudes of the studied values does not exceed 10 %. Let us note at the same time that the coordinate of mass center of injected fuel $X_{цт}$ is at a distance corresponding approximately to a half of jet range L. This note is true for the whole time of injection. Therefore, the irreversible accumulation of great bulk of fuel in the jet head proposed by some authors is not confirmed either by the experiment or by computation by the program CyberDiesel.

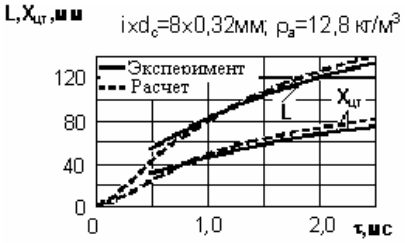

Fig. 4. *Characteristics of jet range and position of jet mass center*

Эксперимент – Experiment; Расчет – Design

The feature of fuel jet process design is the assumption of gas flow potentiality that allowed using the conformal mapping technique for calculation of field velocity in CC [3]. The equations are formed according to the known Euler principle, theoretically justified and experimentally confirmed [1].

Gas flow in CC was modeled on the basis of the method of superposition of hydrodynamic features which allows obtaining total complex flow potential. The influence of fuel particle motion on gas velocity field is modeled in the form of current from flat dipoles. Total complex potential and total complex velocity for any time moment are calculated by the formulas:

$$\Phi_0(z) = \sum_{i=1}^{i_{тек}} \left[-\frac{E_i}{(z - z_i)} \right] + \Phi_s(z) + \Phi_r(z) \ldots,$$

$$v_0(z) = \sum_{i=1}^{i_{тек}} \left[\frac{E_i}{(z - z_i)^2} \right] + v_s(z) + v_r(z) + \ldots, \qquad (5)$$

where E_i is the dipole intensity; z_i is the coordinate of mass center of i fuel portion; z is the current point on a complex plane; $i_{тек}$ is the number of fuel portion injected into CC at a current stage of calculation by time; $\Phi_s(z)$, $v_s(z)$ are the complex potential and complex gas flow velocity along cylinder axis, caused by piston motion; $\Phi_r(z)$, $v_r(z)$ are the complex potential and complex gas flow velocity in the direction perpendicular to cylinder axis.

Influence of drop flow dynamics on gas velocity field is expressed by dipole intensity loss at the design pitch by time $\Delta\tau$ which is determined as the difference of dipole intensities in initial and final quasi-stationary flow states:

$$\Delta E_{\tau,\tau+\Delta\tau} = 2\pi[(w_{к\,i} - w_{a\,i})_\tau - (w_{к\,i} - w_{a\,i})_{\tau+\Delta\tau}]R_i^2, \quad (6)$$

where R_i is the effective radius of i design portion of fuel drops.

Gas flow directed along cylinder axis represents a plane-parallel flow the velocity of which on piston surface equals the velocity of its motion and on cylinder cover surface equals zero. This rate changes along motion direction occurs by linear dependence. Complex potential of this flow is determined:

$$\Phi_s(z) = k_s e^{-j\vartheta} z,$$

where k_s is the real quantity depending on current piston rate and its current position in CC, at piston motion to VMT at piston motion from VMT; k_s sign depends on current direction of piston rate; ϑ is the angle between the nozzle hole axis and cylinder cover surface; j is the imaginary unit.

Complex potential of radial flow is calculated by the formula

$$\Phi_r(z) = k_r e^{-j\vartheta} z,$$

where k_r is the real quantity depending on piston current rate and its current position in CC; k_s sign depends on current position of piston rate.

Complex potential and complex velocity of the flow subject to additional potentials caused by flowing around CC walls are calculated by the formulas:

$$\Phi(z) = \Phi_0(z) + \Delta\Phi_r(z) = \Phi_0(z) + f_1[g(z), \Phi_0(z)],$$
$$v(z) = v_0(z) + \Delta v_r(z) = v_0(z) + f_2[g(z), v_0(z)], \quad (7)$$

where $g(z)$ is the function of conformal mapping of streamlined surface in unit circumference. Modeling the problems flowing round the CC profile of a complicated form (for which it is impossible to find a uniform function of conformal mapping), it should be divided into several simple elements (circular arcs, straight lines etc.), for which such functions are known.

Formulas (5–7) are the basis of modeling velocity field of actuating medium which influences greatly the formation of the field of concentrations in CC; therefore, it influences the character of further preflame reactions as well as heat release characteristics.

Algorithm of preflame reactions is implemented by using theoretical developments [1]. It takes into account the so-called chain and thermal acceleration of reactions as well as dependence of their velocities on agent local concentrations. The design research of gas phase temperature field in vaporizing fuel jet of diesel engine DN23/30 by the time moment 0,25 ms from the beginning of injection (nozzle hole axis is horizontal) is introduced in Fig. 5. As it is seen from the Figure, temperature drop is observed in the jet. And, temperature gradient in that part of the field, which is occupied by the jet, is directed from a certain center being on the axis. The results of field temperature calculations for the time moments close to termination of ignition delay period allow determining the position of flame seat.

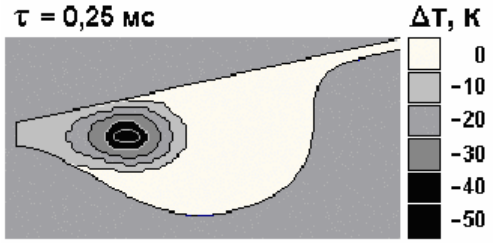

Fig. 5. *The design temperature field in CC*

Fuel combustion and nitrogen oxide emission in combustion residues are calculated using kinetic equations. The parameters, average in cylinder (pressure, temperature, a portion of degraded fuel, mass of formed NO), are calculated by integrating proper local parameters.

The example of comparison of the design indicator diagrams and heat release characteristics with proper experimental data is given in Fig. 6. One can see that deviation of the design pressure values from the experimental ones does not exceed 1 MPa that corresponds to maximal relative error less than 10 %. Relative errors of temperature and heat release characteristics do not exceed 10 and 20 %, respectively.

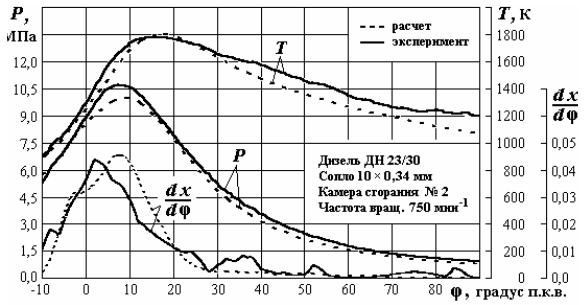

Fig. 6. *The example of the design and experimental characteristics of pressure, temperature and relative velocity of heat release*

Расчет – Design; Эксперимент – Experiment; Дизель – Diesel engine; Сопло – Nozzle; Камера сгорания – Combustion chamber; Частота вращения – Rotation frequency

Thus, the investigations showed that the results of mathematical modeling of fuel supply and intracylinder processes (including elementary processes, intermediate and closing stages of a complex of stages) coincide rather satisfactorily with the experiment results. It means that use of the proposed program CyberDiesel in diesel engineering practice allows solving the questions of agreement of constructive and adjusting parameters of diesel engine and achieving, owing to this increase, its techno-economic and ecological indices.

REFERENCES

1. Gavrilov V.V. Methods of improving carburetion and combustion in marine diesel on the basis of mathematical and physical modeling of local intracylinder processes: Abstract of a thesis ... of doctor of tech. science. – St.-Petersburg: SPSMTU, 2004. – 43 p.
2. Diesel engine operation in under field conditions / A.K. Kostin, B.P. Pugachev, Yu.Yu. Kochenev; ed. by A.K. Kostin. – Leningrad: Mashinostroenie, 1989. – 284 p.
3. Schukin P.A. Complex mathematical model of operation of diesel engine with volumetric carburetion. Abstract of a thesis ... of a cand. of tech. science. – St.-Petersburg: TsNIDI, 1999. – 22 p.

Received on 15.01.2007

UDC 620.18:669.14

THIN STRUCTURE OF STEEL St52,3N AND POSSIBLE REASONS OF DEFECT OF LARGE-CAPACITY BILLETS AT «YURMASH»

V.I. Danilov*, D.V. Valuev, Yu.F. Ivanov**, A.M. Apasov

Technological institute, TPU branch, Yurga
E-mail: mchmyti@rambler.ru
*Institute of physics of strength and material science of RAS SD, Tomsk
**Institute of high-current electronics of RAS SD, Tomsk
E-mail: dvi@ispms.tsc.ru

Electron-microscopic and x-ray investigations of structurally-phase and intense-deformed condition of material made of defective and conditional forged billet at «Yurmash» have been carried out. It is ascertained that in steel made from the defective forged piece the fraction of perlite is 1,5...2 times higher and lamellar perlite prevails. Local long-range tensions in both conditions of material are commensurable with fluidity limit. The content of sulfides is considerably higher in the steel made from the defective billet. They are located in the body of ferrite grains and along the interfaces. In the material made from the conditional forging they are located only inside of grains. The scalar density of dislocations in ferrite grains and in ferrite layers of perlite of the defected billet is one and a half time higher than in conditional metal. All the totality of the listed above circumstances allows stating that the main cause of cracking of large-capacity billets made of steel St52,3N is not a full conformity of the chemical compound to branded requirements.

1. Introduction and prestarting procedures

In the article [1] the following conclusion was drawn – it is impossible to determine the reasons of cracking the forgings of steel St52,3N without estimation of mode of deformation, precision investigations of structure, the analysis of defective subsystem state and ascertainment of crystal-chemical nature of secondary phase precipitations. Really, optical microscopy does not allow even determining precisely the perlite morphology, although, granular perlit is more preferable than lamellar one in critical product [2]. The most important factor determining article structural strength are the internal residual stresses [3] which are not metallographically controlled at all. Besides, secondary phase precipitations are qualified in steels by metallographic technique only as nonmetallic inclusions of proper point [4], however, carbide, oxide, sulfide and phosphide phases influence differently the operating characteristics. All the listed problems may be solved by the methods of X-ray diffraction analysis and transmission electron microscopy.

In this work the electron microscopic investigations were carried out at transmission microscope UEMV-125K in light and dark fields. Electron diffraction patterns of reflexes in dark field were recorded for analyzing crystal structure of secondary phases. Foils for researches were cut by electric-spark method from samples which were used before in metallographic analysis. Final preparations of foils were carried out by electropolishing. Thin structure of steel made of defective and conditioned forging was studied. A type of dislocation substructure in ferrite grains and perlite ferrite layers, perlite colony structure, shape, sizes, position and composition of secondary phase particles, level of internal long-range stresses were determined.

2. The results of electron microscopy of defective forging material

An attempt to use the X-ray diffraction analysis for identifying secondary phases and estimating internal stresses turned out to be unsuccessful. It is, probably, connected with the fact that sulfide, phosphide and oxide phases present in steel in mass concentrations lower than the detection limit by the X-ray method. Carbide phase is presented by cementite which is not roentgenographically detected at α-Fe. Internal stresses of the I kind may be defined only in the whole article and the stresses of the II kind turned out to be lower than the level of reliable identification both in defective and conditioned metal. One succeeded in ascertaining that lattice parameter of defective forging metal is higher, that indicates the increased content of interstitial impurities – carbon, first of all. Therefore, the main attention was given to electron microscopic investigations.