Materials Physics and Mechanics 32 (2017) 305-311 Received: April 26, 2017

TESTING OF STEEL 45 UNDER COMPLEX LOADING ALONG THE CYLINDRICAL SCREW TRAJECTORIES OF DEFORMATION

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Abstract. The results of the experiment on complex loading of a thin-walled tubular steel specimen with three parameter action of axial force, torsion, and internal pressure are presented. The experiment was carried out on A.A. Ilyushin's testing complex SN-EVM. The program of the experiment in the deformation space is a cylindrical, helical trajectory with a displaced center of a screw curvature. Scalar and vector properties of the material steel 45 were investigated.

Keywords: plasticity; complex loading; trajectory of deformation; helical trajectory; scalar and vector properties of material; thin-walled tubular steel.

1. Introduction

The experimental investigations conducted for studying of patterns and effects of structural materials deformation the behind elastic limit at compound stress condition and under disproportionate loading are an important component of mechanics of deformable solids and plastic theory. The phenomenological approach is the basis for the development of new mathematical models of deformation of materials behind elastic limit, and also for certification and assessment of limits of applicability of the modern theory of plasticity existing models.

A large number of systematic experimental investigations was carried out under materials deformation along flat multilink piecewise and broken rectilinear and curvilinear trajectories of constant and variable curvature [1-10]. Tests at uniaxial ratcheting and difficult cyclic deformation on the closed trajectories [11-15] represent a special case of the sign variable theory of plasticity. The experiments executed on space trajectories of deformation of constant and variable curvature are practically absent [1, 3, 16, 17]. Series of tests on thin-walled tubular specimens made of 45 steel at rigid loading along the dimensional trajectories in deviatory space of deformations $Э_{(3)}$ showing an uncommon connection between tension and deformations at the elastoplastic deformation of material has been carried out in TvSTU mechanical laboratories. In the series of the tests at different parameters of internal geometry were implemented:

– cylindrical screw trajectories of constant curvature and torsion with screw center of curvature in datum origin on the plane $Э_1 - Э_3$;

– cylindrical screw trajectories of constant curvature and torsion with the displaced screw center of curvature on the plane $Э_1 - Э_3$;

– the conic screw trajectories of variable curvature and torsion $Э_1 - Э_3$ presenting folding and unfolding Archimedes's spirals in the planes $Э_1 - Э_3$.

The screw axis in all experiences had been oriented in the direction of coordinate $Э_2$. Testing was carried out on the Ilyushin's automatic testing complex SN-EVM, realizing the three-parametrical impact on a specimen (axial tension-compression, torsion, and internal pressure) in the automatic mode according to the set deformation program. When carrying out deformation tests were measured by means of the extensometer working together with the SN-EVM complex.

2. Technique of experiment and main equations

The technique of experimental studies conducting is based on the A. A. Ilyushin's theory of elastoplastic processes [1, 2, 18, 19], where deviator of tension and deformations with components

$$S_{ij} = \sigma_{ij} - \delta_{ij}\sigma_0, \quad Э_{ij} = \varepsilon_{ij} - \delta_{ij}\varepsilon_0, \ (i, \ j = 1, 2, 3) \tag{1}$$

are presented in the form of tensions $\bar{\sigma}$ and deformations $\bar{Э}$ vectors of forming in five-measured deviatory space

$$\bar{\sigma} = \sigma\hat{\sigma} = S_k \hat{i}_k, \quad \bar{Э} = Э\hat{Э} = Э_k \hat{i}_k \quad (k = 1, 2, 3), \tag{2}$$

where σ_{ij}, ε_{ij} are components of stress and deformations tensors, δ_{ij} is the Kronecker's symbol, $\sigma_0 = \sigma_{ii}/3$, $\varepsilon_0 = \varepsilon_{ii}/3$ are average tension and deformation; $\hat{\sigma}, \hat{Э}$ is unit vectors;

$$\sigma = \sqrt{S_k S_k} = \sqrt{S_1^2 + S_2^2 + S_3^2}, \quad Э = \sqrt{Э_k Э_k} = \sqrt{Э_1^2 + Э_2^2 + Э_3^2} \tag{3}$$

are modules $\bar{\sigma}$ and $\bar{Э}$; $\{\hat{i}_k\}$ is orthonormalized motionless basis; S_k, $Э_k$ are coordinates of vectors $\bar{\sigma}$ and $\bar{Э}$ in the basis, for which

$$\begin{aligned} &S_1 = \sqrt{\frac{3}{2}} S_{11} = \sqrt{\frac{2}{3}}(\sigma_{11} - \frac{1}{2}(\sigma_{22} + \sigma_{33}), \ S_2 = \sqrt{2}\left(S_{22} + \frac{1}{2}S_{11}\right) = \frac{1}{\sqrt{2}}(\sigma_{22} - \sigma_{33}), \\ &S_3 = \sqrt{2}\, S_{12} = \sqrt{2}\,\sigma_{12}; \\ &Э_1 = \sqrt{\frac{3}{2}} Э_{11} = \sqrt{\frac{3}{2}}\left(\varepsilon_{11} - \varepsilon_0\right), \ Э_2 = \sqrt{2}\left(Э_{22} + \frac{1}{2}Э_{11}\right) = \frac{1}{\sqrt{2}}\left(\varepsilon_{22} - \varepsilon_{33}\right), \\ &Э_3 = \sqrt{2}\, Э_{12} = \sqrt{2}\,\varepsilon_{12}. \end{aligned} \tag{4}$$

In this case, history of stresses and deformations tensors changing is represented geometrically in vector (deviatory) spaces of forming in the form of images of the processes containing trajectory, and its points assigned with lengths of arc s or Σ characteristics of process: vectors $\bar{\sigma}$ or $\bar{Э}$ and their increments, and also scalar parameters (temperature, average stress σ_0 and deformation ε_0 etc). At the same time, the connection between tensions and deformations is described by the scalar properties, characterizing connection between invariants of deviator of tensions and deformations, and the vector properties, characterizing misalignment of deviator of tensions, deformations and their increments. The provision of vector of tension $\bar{\sigma}$ is defined by unit vector for which

$$\hat{\sigma} = \frac{\bar{\sigma}}{\sigma} = \cos\vartheta_1 \hat{p}_1 + \sin\vartheta_1(\cos\vartheta_2 \hat{p}_2 + \sin\vartheta_2 \hat{p}_3), \tag{5}$$

where unit vectors of the Frenet frame $\{\hat{p}_k\}$

$$\hat{p}_1 = \frac{d\bar{Э}}{ds}, \quad \hat{p}_2 = \frac{1}{\kappa_1}\frac{d^2\bar{Э}}{ds^2}, \quad \hat{p}_3 = \frac{1}{\kappa_2}\left[\kappa_1 \frac{d\bar{Э}}{ds} + \frac{d}{ds}\left(\frac{1}{\kappa_1}\frac{d^2\bar{Э}}{ds^2}\right)\right], \ \ldots; \tag{6}$$

κ_1, κ_2 are parameters of curvature and torsion of the internal geometry of trajectory of deformation; ϑ_1 is vector $\bar{\sigma}$ approach angle with a tangent vector $\vec{p}_1$ to deformation trajectory; ϑ_2 is the deplanation corner characterizing vector $\bar{\sigma}$ deviation from vector $\vec{p}_2$ projected to the normal plane $\vec{p}_1\vec{p}_3$. At the creation of experimental dependencies, it is necessary to consider features of the behavior of both scalar, and vector material properties.

Cylinder thin-walled shells from steel 45 in the condition of delivery which had the $h = 1$ mm wall thickness, $r = 15,5$ mm radius of the median surface of the cross-section, and $l = 110$ mm length of working part used as physical models for researching on the SN-EVM testing complex. In walls of specimens at a relation of r / h homogeneous flat stress condition is implemented. The material of specimens sufficiently was initially isotropic that was confirmed by basic tests at simple loading on trajectories like the "central fan" including tests on stretching, compression, torsion and internal pressure. While processing results of experimental data, dependencies [1, 3] were used to identify components of tensors of deformations ε_{ij} $(i, j = 1, 2, 3)$ and tension σ_{ij}.

$$\begin{cases} \varepsilon_{11} = \dfrac{\Delta l}{l}, \ \varepsilon_{22} = \dfrac{\Delta r}{r}, \ \varepsilon_{12} = \dfrac{r\psi}{2l}, \ \varepsilon_{13} = \varepsilon_{23} = 0, \\ \varepsilon_{33} = -(\varepsilon_{11} + \varepsilon_{22}) + \dfrac{\sigma_0}{K}, \ \varepsilon_0 = \dfrac{1}{3}(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}), \end{cases} \tag{7}$$

$$\begin{cases} \sigma_{11} = \dfrac{P}{2\pi rh}, \ \sigma_{22} = q\dfrac{r}{h}, \ \sigma_{12} = \dfrac{M}{2\pi r^2 h}, \ \sigma_{33} \approx 0, \ \sigma_{13} = \sigma_{23} = 0, \\ \sigma_0 = \dfrac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}), \ K = \dfrac{E}{3(1-2\mu)}, \end{cases} \tag{8}$$

where Δl and Δr − increments of l and r; ψ − cross-section turning angle; P − the stretching axial force; q − intensity of internal pressure; M − torque; E − Young's modulus; μ − Poisson's ratio; K − Bulk modulus. When processing experimental data the condition of incompressibility of material ($\varepsilon_0 = 0$), was accepted inasmuch as with the advent of plastic deformations μ_p the coefficient of cross deformation quickly approached value $\mu_p = 0,5$.

The article is about the program of deformation along cylindrical screw trajectory with the displaced screw center of curvature from the origin on the plane $Э_1 - Э_3$ (fig. 1-4) realized in tests.

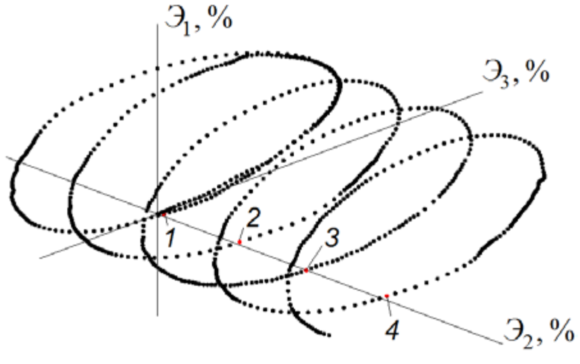

Fig. 1. Space trajectory of deformation.

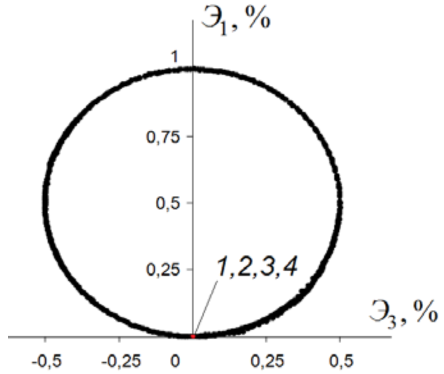

Fig. 2. Deformation trajectory on the plane $Э_1 - Э_3$.

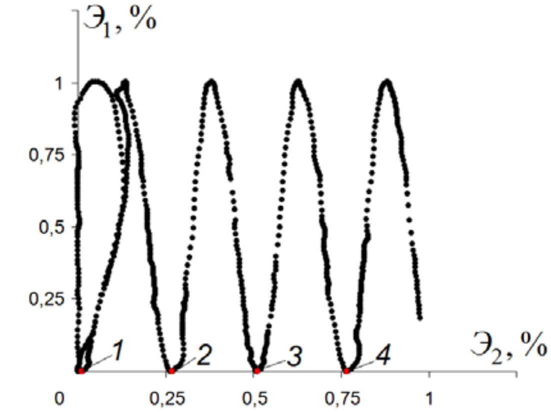

Fig. 3. Deformation trajectory on the plane $Э_1 - Э_2$.

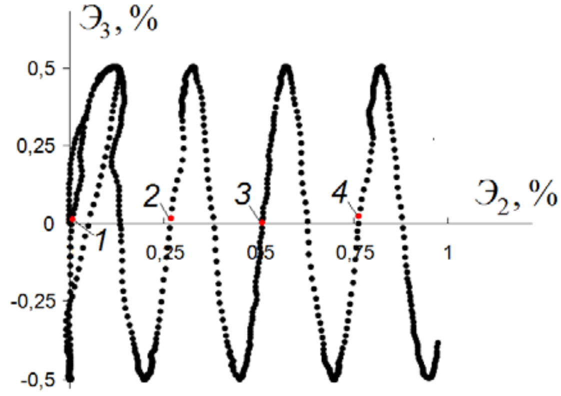

Fig. 4. Deformation trajectory on the plane $Э_2 - Э_3$.

The trajectory with constant curvature in the form of radius circle $R = 0,5\,\%$, whose pole coordinates were $Э_1^* = 0,5\,\%$, $Э_3^* = 0$ and curvature was $\kappa_1 = 1/R = 200$ was implemented at the first site, tension with torsion jointed in the experiment. After whole turnover of the circle by means of internal pressure on the second site deformation along axis $Э_2$ along screw trajectory in the number of 4 incomplete rounds with propeller pitch $H = 0,25\,\%$ and parameter of torsion $\kappa_2 \approx 15,7$ was implemented. The digits 1, 2, 3, 4 in figures 1-4 have designated points of the beginning of the first and the subsequent rounds of the screw. The experience in the mode of continuous specimen deformation with fixed speed $\dot{\varepsilon} = 10^{-6}\ \text{s}^{-1}$, allowing to choose short-term creep of material at standard temperature continued for more than 9 hours.

For implementation of cylindrical screw trajectory on the second site of the program of experiment the Cartesian coordinates of vectors on the SN-EVM automated complex were set in the form of [1, 3]

$$Э_1 = Э_1^0 + R\sin\varphi, \quad Э_2 = Э_2^0 + b\varphi, \quad Э_3 = Э_3^0 + R\cos\varphi, \tag{9}$$

where $Э_1^0$, $Э_2^0$, $Э_3^0$ − Cartesian coordinates of curvilinear part of trajectory pole; φ is the polar corner counted from axis $Э_1$ against the course of the hour hand; $b = H/2\pi$. For presented in fig. 1-4 trajectories $Э_1^0 = 0,5\,\%$, $Э_2^0 = Э_3^0 = 0$. As propeller pitch is $H = 0$ we have $b = 0$, and from (9) the circle equation realized on the first site follows.

When processing results of experimental studies on strain and stress vectors coordinates forming were defined by components of tensors on formulas (4), and vector modules on formulas (3). For definition of approach angles ϑ_1, deplanation angles ϑ_2 and the contact angles ψ_1, characterizing the influence of vector material properties on deformation process were used expressions

$$\cos\vartheta_1 = \hat{\sigma}\hat{p}_1 = \frac{1}{\sigma\dot{s}}\left\{S_2 b + R\left[S_1\cos\varphi - S_3\sin\varphi\right]\right\},$$

$$\sin\psi_1 = \hat{\sigma}\hat{p}_3 = \frac{1}{\sigma\dot{s}}\left\{S_2 R - b\left[S_1\cos\varphi - S_3\sin\varphi\right]\right\}, \qquad \sin\vartheta_2 = \frac{\hat{\sigma}\hat{p}_3}{\sin\vartheta_1} = \frac{\sin\psi_1}{\sin\vartheta_1}, \tag{10}$$

where

$$\dot{s} = \sqrt{R^2 + b^2}, \quad \sin\varphi = (Э_1 - Э_1^0)/R, \quad \cos\varphi = (Э_3 - Э_3^0)/R. \tag{11}$$

3. Experimental results

In fig. 5-11 experimental results of testing of a tubular specimen on the program submitted in fig. 1-4 are presented. In fig. 5-8 the response in space of tension $S_{(3)}$, in fig. 9 local charts of deformation on coordinates $S_k - \text{Э}_k$, in fig. 10 - the general charts of deformation $\sigma - \text{Э}$ and $\sigma - s$, the characterizing scalar material properties, where s is the length of the arc of deformation trajectory are presented. The dependences of corners ϑ_1, ϑ_2 and ψ_1 on s characterizing vector material properties is given in fig. 11.

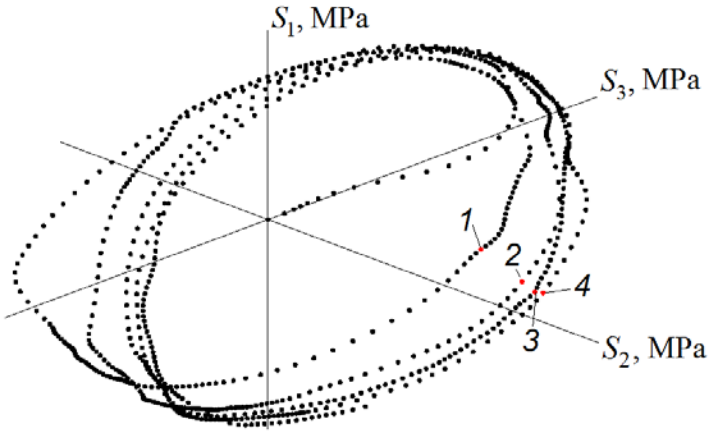

Fig. 5. A response in space of tension $S_{(3)}$.

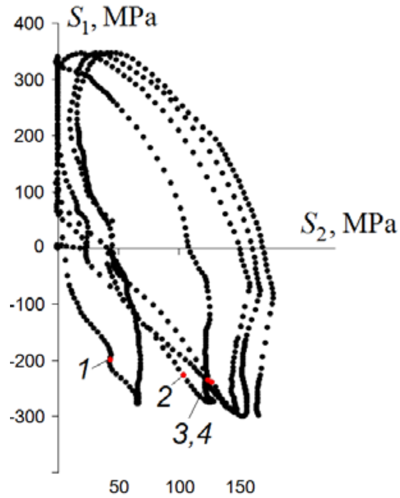

Fig. 6. Response to the plane $S_1 - S_2$.

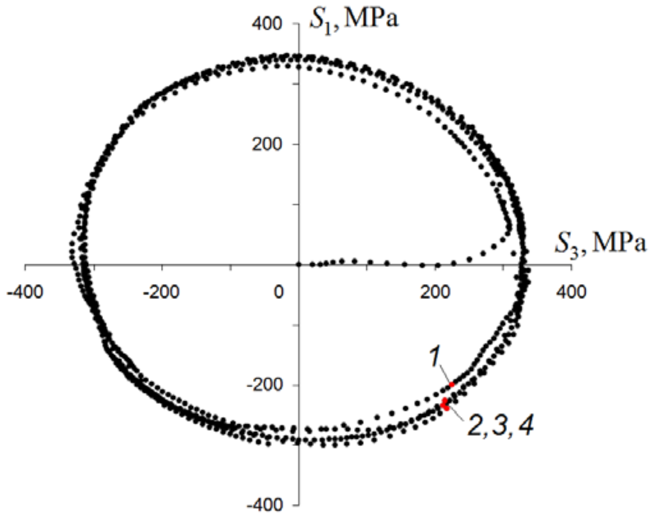

Fig. 7. Response to the plane $S_1 - S_3$.

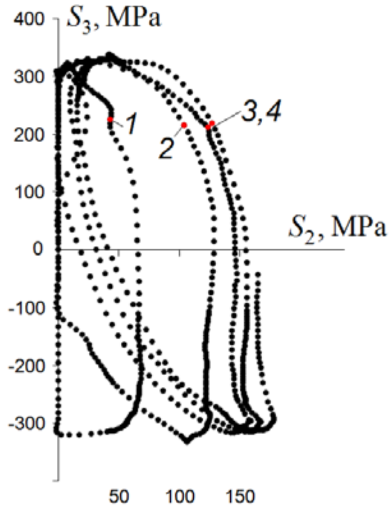

Fig. 8. Response to the plane $S_3 - S_2$.

While deformation on the site of circle the Э_2 - effect [1], which is followed by the emergence of deformation anisotropy and growth of component Э_2, which peak value was $0{,}13\,\%$ was observed. At further deformation value of Э_2 decreased, and before screw trajectory was close to zero.

On the chart $\sigma - s$ (fig. 10) on the site of the circle and four rounds five "direct" dives of tension and on the chart $\sigma - \text{Э}$ are five "return" dives of partial elastic unloading are traced. This obviously differs from the Odkqist-Ilyushin's law of hardening $\sigma = \Phi(s)$. The size of tension dives decreased each time: on the site of circle the size of dive was $\Delta\sigma \approx 54\,\text{MPa}$, on the last spiral turn – $\Delta\sigma \approx 18\,\text{MPa}$. Material in the course of plastic deformation, in general, has received hardening, but it was insignificant and was only 45 MPa that at the value of liquid limit $\sigma^{\text{T}} \approx 315\,\text{MPa}$ corresponds to the value of $\sigma \approx 360\,\text{MPa}$.

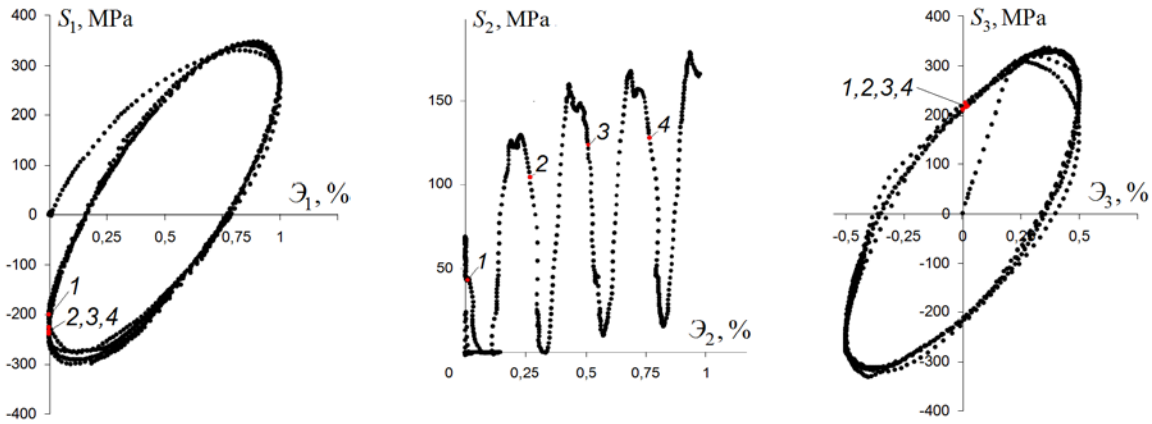

Fig. 9. Local charts of deformation $S_1 - Э_1$, $S_2 - Э_2$, $S_3 - Э_3$.

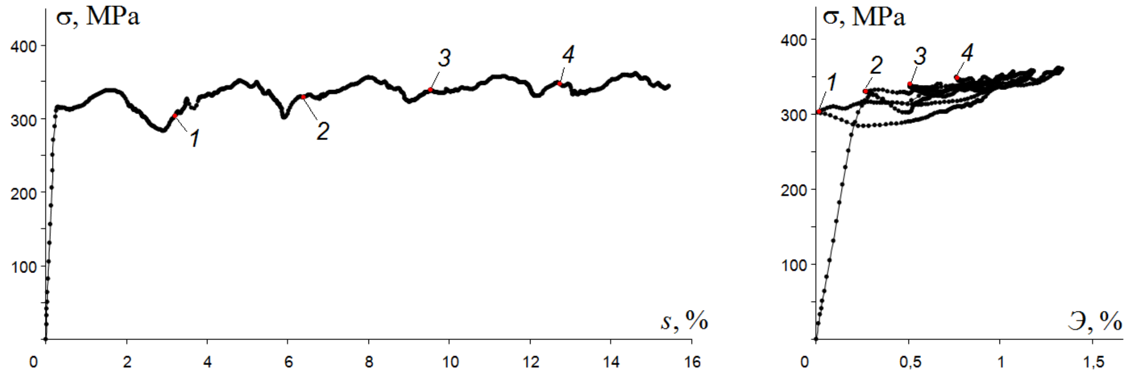

Fig. 10. General charts of deformation $\sigma - s$, $\sigma - Э$.

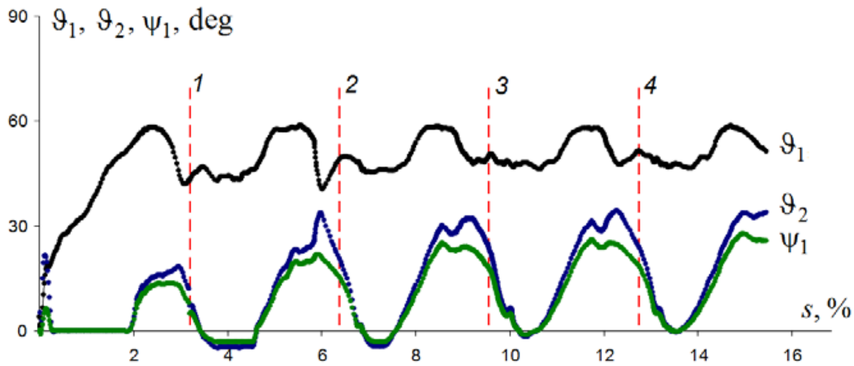

Fig. 11. Charts $\vartheta_1 - s$, $\vartheta_2 - s$, $\psi_1 - s$.

Change of coordinate size S_2 on screw rounds has practically not impacted on coordinates S_1 and S_3 (see fig. 7). At the same time, explicit frequency of local charts of stretching compression $S_1 - Э_1$ and torsion $S_3 - Э_3$ is observed (see fig. 9). Also, explicit frequency on rounds of the screw is observed for corners ϑ_1, ϑ_2 , and ψ_1. Peak values of ϑ_2 and ψ_1 corners was 33° and 25° respectively. Values of the approach angle ϑ_1 averaged 50°, therefore elementary deformation work $dA = \overline{\sigma} d\overline{Э} = \sigma ds \cos\vartheta_1$ for corners $\vartheta_1 < 90^\circ$ is $dA > 0$. It means that there is an active deformation process at all sections of the given trajectory.

4. Conclusion

The experimental data presented in the article for dimensional elastoplastic processes of deformation are necessary for the solution of an important problem of reliable creation of approximations of functionalities of the plasticity of the general defining ratios of the theory of processes [1, 2], and the adequate description of difficult space processes of loading of continuous environments.

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