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KINETICS OF TEMPERATURE AND PLASTIC STRAINS DURING HEATING A LONGITUDINAL EDGE OF A STEEL BAND BY MOVING WELDING HEAT SOURCE

The paper presents the results of the finite element modeling of kinetics of temperature, linear $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ and shear $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ plastic strains in band made from 08nc steel with dimensions of 600×60×4 mm, during its heating along the longitudinal edge axial line of plane by a welding arc in argon (TIG-welding).

The purpose of the paper was to find an idea of a technological solution for reducing the residual flexure of the band axial line, combined with the stage of the main technological process of the steel band heating. [dx.doi.org/10.29010/084.7]

Keywords : *steel band; J. Goldak moving heat source; kinetics of temperature and plastic strains.*

Introduction

Heating of the longitudinal edge of the band is used in manufacturing to solve various technological problems during the process of welded structures fabrication in shipbuilding, building and other industries.

In the welding stresses and strains theory, the problem of welding heating of the longitudinal edge of the band is considered as classical, it has received much attention in educational literature for students of welding specialties and specializations from the standpoint of studying and mastering the mechanism of the residual stress-strain state (SSS) forming in the band.

The residual SSS in the band made from 08пс steel with dimensions of 600×60×4 mm after heating it along the longitudinal edge and complete cooling had been studied by us using the method of finite element modeling earlier. Calculation results were compared with experimental data. These results were presented in [1, 2].

Under laboratory conditions, experiments of the band heating were carried out on an original specialized welding equipment, designed and fabricated at the Welding Production Department of NTUU "Igor Sikorsky Kyiv Polytechnic Institute" [1].

In previous researches [1, 2] it had been established that in the band middle part along its length, under the specified, technologically optimal, heating mode of the longitudinal edge with heat input rate of 120 J/mm, after 1200 s since the start of heating, almost an uniaxial residual stress state occurs with orientation of its parameters along the X axis in the specified XYZ coordinate system, as shown in Fig. 1. Other components of the stress state, in some cases, can be neglected due to their smallness. However, this cannot be said about the residual strain state with respect to axial and shear plastic strains [2].

From the welding stresses and strains theory [3-8], it is known that the reason of formation in the welded designs, including the band under consideration, the residual SSS and all caused with it problems in welded designs is the formation of a complex field of residual plastic strains in the design during welding. For geometrically simple welded joints and designs, these strains are well studied by both calculated and experimental methods. A lot of attention had been attended for developing the ways to reduce or prevent the formation of the residual SSS in designs. However, this important scientific-technical problem is still relevant, and therefore scientific researches in this direction continues.

The residual SSS in the welded design is formed from a chain of serial temporary states of the temperature fields and plastic strains, that is, from their kinetics. This implies the practicability of studying and analyzing kinetics of temperature and plastic strains during welding, including the steel band considered in this paper. The complex of the obtained results and their subsequent analysis probably may indicates the direction of searching for new technological solutions combined with the main technology of the band processing in order to reduce the residual SSS, including the flexure of the longitudinal axis of the band with the heated longitudinal edge.

Analysis of kinetics, i.e. changing of the temperature, axial $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ and shear $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ plastic strains at various points over time t, during the processes of heating and cooling of the longitudinal edge of the band, in this paper, were carried out on the basis of the time dependences of temperature and plastic strains obtained using the finite element method (FEM). Charts were plotted for specified cross sections with preset x coordinates. Cross sections were selected on the lateral plane of the geometric model of the band (plane z = 2 mm in the specified XYZ coordinate system, Fig. 1). Cross sections on the band mesh model were marked by the mesh nodes that we are interested in. In total 7 cross sections with coordinates x = 60, 100, 200, 300, 400, 500 and 540 mm were analyzed in this paper with subsequent processing and generalization of the obtained results.

Investigation problems

The purpose of the paper consists of two parts. The first part is dedicated for research and founding of tendencies and causes of the adverse progress of thermo-deformation processes during heating and cooling of the band by a moving welding arc over the plane of the longitudinal edge. Such heating of the edge of the band with a preset heat input rate leads to the formation in its mid-thickness plane of the residual flexure of a considerable value. To achieve the goal of the first part, a thorough and large-scale analysis of kinetics of temperature, temporal axial and shear plastic strains in the band is necessary. The second part of the paper's goal is to propose and substantiate the idea of the technological solution which is combined with the main technological operation of the welding processing of the band, which will allow significantly reduce the residual flexure of the band after heating its longitudinal edge by moving welding arc.

The following research tasks were set in the paper:

- provide the solution of coupled thermo-elasto-plasticity problem to determine the temperature and residual linear axial and shear plastic stains in the band made from 08пс steel with dimensions of 600×60×4 mm during heating its longitudinal edge by moving welding heat source (TIG-welding);
- to obtain new calculation data of the temporal dependence of temperature in selected nodes of the band cross section, as well as axial $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ and shear $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ plastic strains in the specified cross sections of the band middle part along its length;
- discussion and analysis, in general, of all obtained calculation results and the formulation of general conclusions.

Main part

In the specified for the calculations rectangular coordinate system *XYZ*, the band with a heated upper longitudinal edge is shown in Fig. 1. The edge is heated during the main technological process, which determines the purpose of the band or the method of its fabrication. The bottom edge is not heated. Heating of the upper edge leads to, that in the residual state, a bending of the band occurs in its middle plane *XY* with the formation of a maximum flexure of the axial line in the middle cross section. The flexure of the band axial line depends on its geometric dimensions, the heating mode and can be significant. Location of the cross sections by the length of the band is determined by the x coordinate within $0 \leq x \leq 600$ mm range.

The mesh of the geometric model of the band had been created in such way, that the finite cubic elements, located close to the heated edge of the band, had edge size of 1 mm. As the distance from the heated edge increases, the edge size of the finite elements was increased up to 4 mm. Finite element model of the band consists of 49976 cubic elements. The material of the band is 08пс steel by GOST 1050-88 with an ultimate strength of 280 MPa and ferrite metal structure after fabrication condition. The temperature field for heating the longitudinal edge of the band was modeled by J. Goldak volumetric heat source [9].

Heating of the band edge was done in a single pass on a specialized welding equipment [1] with numerical program control of the welding torch movement on the mode: the heating source velocity is 4 mm/s, the welding current is $I = 60$ A, the arc voltage is $U = 10$ V, arc efficiency - $\eta = 0.8$, heat input rate - 120 J/mm. Heating duration of the longitudinal edge of the band with a 600 mm length is 150 s. This heating mode, for the band of 4 mm thickness, provides a complete melting of the band edge to a depth of 1 mm without allowing molten metal to flow from it. After the heating of the longitudinal edge of the band with subsequent complete cooling and unfixing of the band, which are technologically necessary during heating, the residual SSS is formed in the band. Further researches showed that on the forward and aft edges of the band, two areas along the band length are forming, each of ~ 60 mm length, in which all parameters of the residual SSS are distributed unequal. The length of the band middle part, where the stress state can be considered as almost uniaxial, depends on the ratio of the band length to its width. It is recommended to take the length of the middle part of the band equal to the band length except it's twice width. The residual SSS in the band after heating and cooling of its longitudinal edge according to the heating mode specified above is presented in paper [1]. In this paper, as in the previous one [1], it was assumed that the band is completely cooled after 1200 s since the start of heating of its longitudinal edge. A ~ 20 mm wide zone of residual plastic strains is formed in downwards from the heated edge of the band. Researches have shown that the equal distribution of both the residual linear axial εp_{xx}, εp_{yy}, εp_{zz}, and shear γp_{xy}, γp_{yz}, γp_{xz} plastic stains in any cross section of the middle part of the band along its length. This indicates the quasistationary both for the temperature field during heating of the longitudinal edge and residual SSS for this part of the band. This statement does not applies to the temporary and residual displacements of the various sections of the band, both in the middle and in its end parts, since displacements are integral characteristics of the elasto-plastic strain state. Thus, the temporary or residual elasto-plastic SSS in the middle part of the band can be considered and studied using the distribution of its parameters for the middle cross section of the band at $x = 300$ mm.

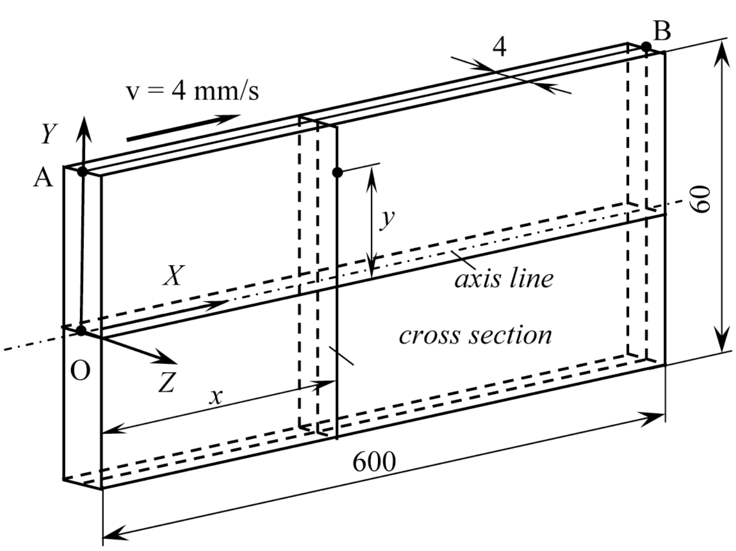

Fig. 1. General view of the band with an upper edge heated along the line *AB*

Charts of kinetics of temperature distribution $T(t)$, axial $\varepsilon p_{xx}(t)$, $\varepsilon p_{yy}(t)$, $\varepsilon p_{zz}(t)$ and shear $\gamma p_{xy}(t)$, $\gamma p_{yz}(t)$, $\gamma p_{xz}(t)$ plastic strains in the nodes of the section at $x = 300$ mm are shown in Fig. 2-13.

First of all, the consideration of kinetics of temperature $T(t)$ in the middle cross section at $x = 300$ mm (Fig. 2) for the most characteristic nodes with coordinates $y = 30$, 29, 28, 26, 24, 22, 20, 18, 16 mm over the time interval $t = 70$-90 s of the heating source movement along the edge of the band will be performed.

At 73 second, the coordinate of the heating source is x-arc = 292 mm, i.e. the source is located in 8 mm from the middle cross section at $x = 300$ mm. At this moment, the temperature at node 47843, with coordinate $y = 30$ mm on the edge of the band is only 85.18 °C. During further heating source

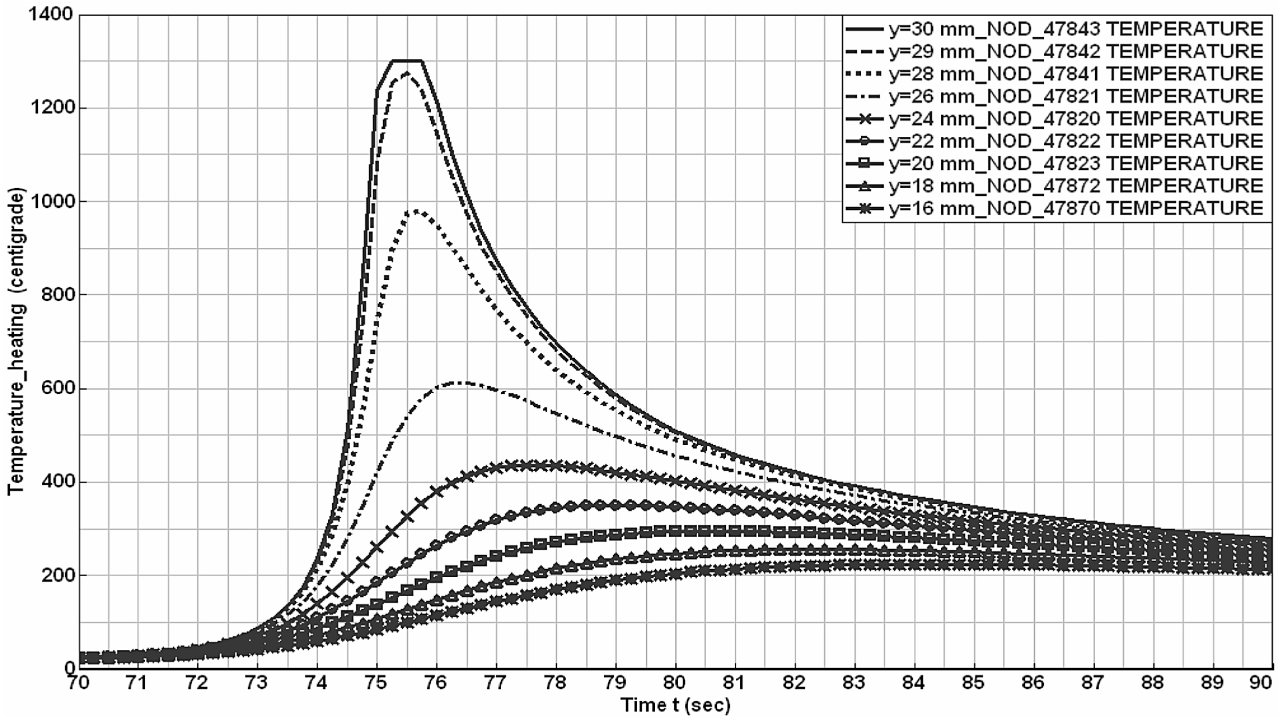

Fig. 2. Kinetics of temperature in the nodes of the band cross section at x = 300 mm in time interval of the heating source movement along the band upper edge

movement, gradient of the temperature changing in the node on the edge increases extremely and at 75 s the temperature in the node reaches 1238.04 °C. This is commensurate with the melting point of the metal of the band 1300 °C, which is reached at the node at 75.25 s and holds at this level up to 75.75 s including. At 75 s, the heating source passes the coordinate of the middle cross section at x = 300 mm and moves further along the edge of the band. From the time moment t = 75.75 s, the node begins to cool and its temperature gradually decreases, as the heat source moves away from the section at x = 300 mm. At 80 s, the heat source is already 20 mm away from the node. In other nodes of the section at x = 300 mm with coordinates y = 20, 18, 16 mm, the temperature slightly increases at this second.

For further analysis, the temperature distribution in the cross section at x = 300 mm for the most heated nodes with coordinates y = 30, 29, 28, 26, 24, 22, 20, 18, 16 mm need to be considered, as heating source approaches the cross section at x = 300 mm (Fig. 3, the heating stage of the node 47843, t = 74-75.5 s) and when heating source moves away from it (Fig. 4, the cooling stage of the node 47843, t = 75.5-80 s).

In this paper, under the heating stage, such location of a bold solid curve is considered with maximum heating of the node 47843 on the edge of the band and the corresponding heating of other nodes of the middle cross section within the distance S = 0-15 mm from the heated edge. This curve sets up at 75.5 s. The process of the cross section heating in the time interval t = 74-75.5 s, are shown on other curves, located below the bold solid curve.

The beginning of the cooling stage is considered as the moment (t = 75.5 s) of temperature decreasing in the most heating node 47843 on the edge of the band (Fig. 4).

At each subsequent moment the temperature curves (dashed, dotted, dash-dotted and other curves) in the highly heated zone near the heated edge continue to decline, indicating the cooling of the active zone of the band. At the same time, in the less heated zone of the band, at distance S = ~ (3-15) mm, the node temperature for other curves increases by ~ 130 °C. Heat from the highly heated zone of the band spreads to the less heated zone and this, as it will be shown below, negatively affects on the magnitude of the residual flexure of the band. It is necessary to prevent spreading of the additional heat into this area of the band (technologically it should be removed away by appropriate cooling) since it counteracts the formation of longitudinal plastic strains of elongation at the cooling stage, which, as it is known [3-7], are necessary for a significant reduction of the residual relative volume of the plastic shortening, which determines the amount of shrinkage force and residual flexure of the band.

Further, kinetics of linear plastic strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ in ten surface nodes of the band mesh model will be analyzed on its lateral surface at z = 2 mm of the middle cross section at x = 300 mm, shown in Fig. 5-7. Nodes with y coordinates from y = 30 mm to y = 12 mm the cross section are shown in

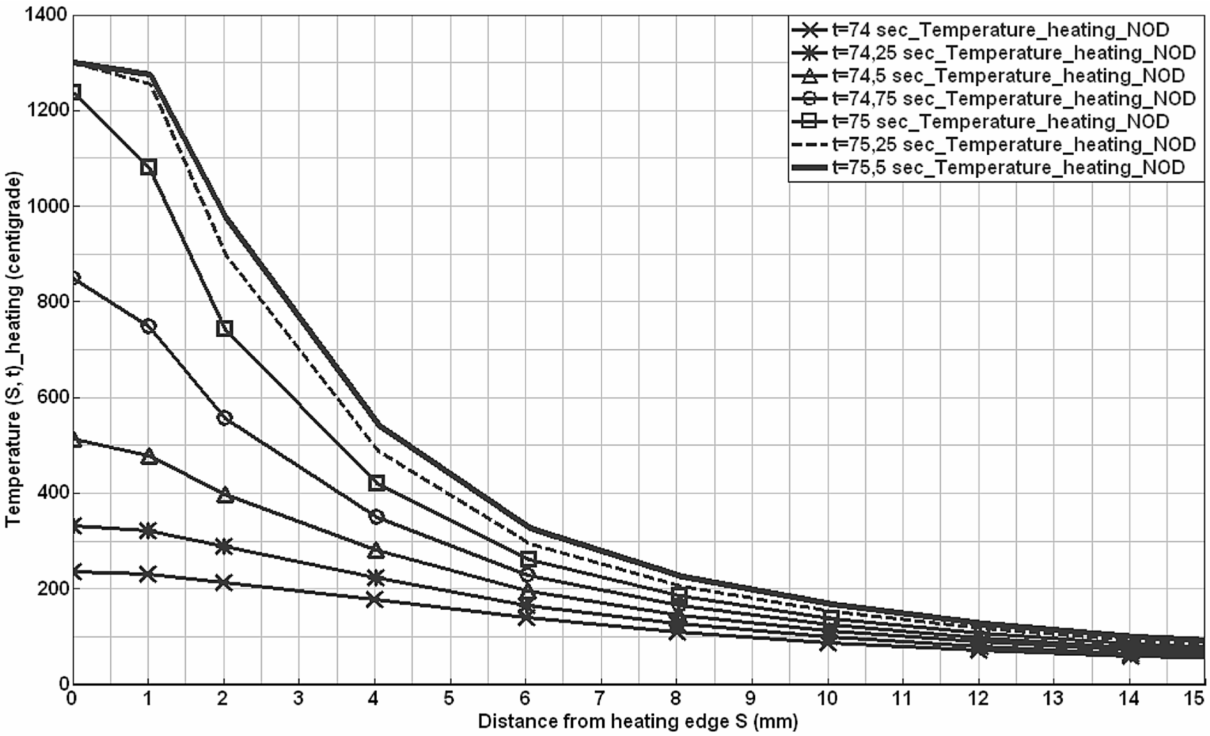

Fig. 3. Temperature in cross section at x = 300 mm during the cooling stage depending on the distance S from the heated edge and the heating time t = 74 - 75.5 s

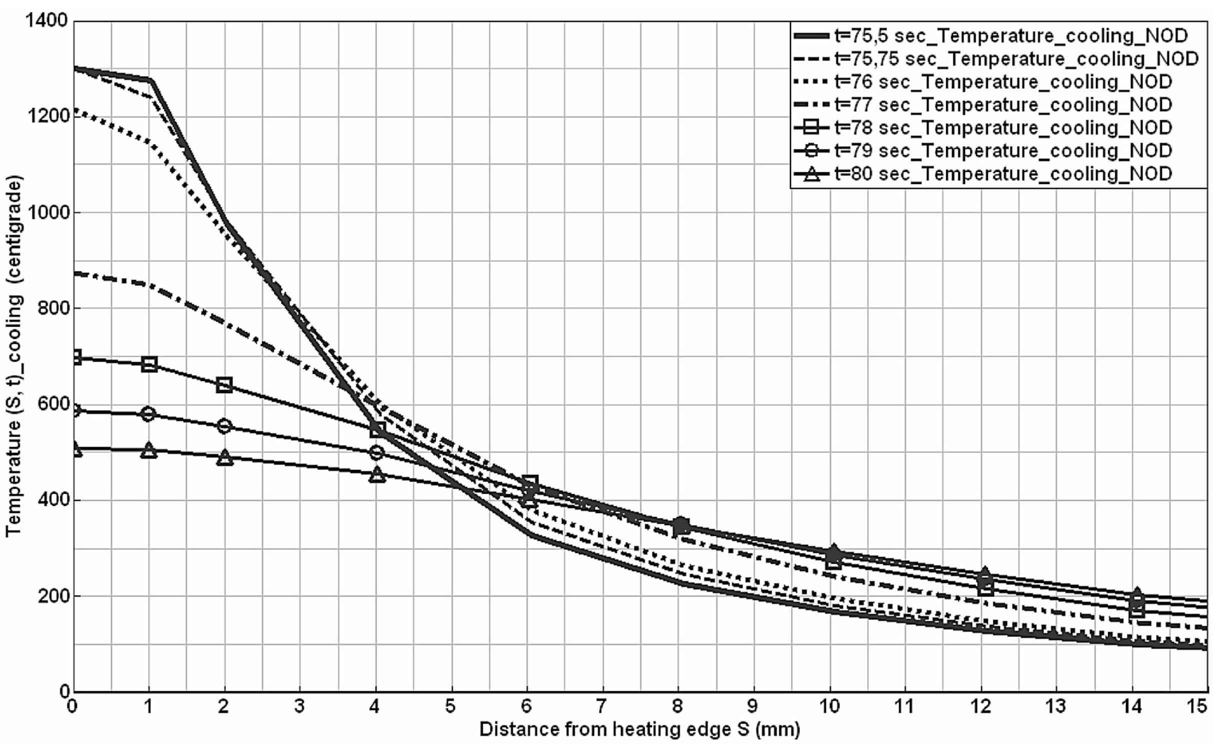

Fig. 4. Temperature in section at x = 300 mm during the cooling stage, depending on the distance S from the heated edge and the heating time t = 75.5-80 s

the legend of the charts in Fig. 5-7. Node with coordinates y = 30 mm, z = 2 mm belongs to the upper heated edge and the lateral surface of the band at the same time. From Fig. 5–7, it can be seen that the greatest gradients of plastic strain changes are correspond to a time interval ~ 73–83 s. At time interval ~ 83–100 s, the gradients of strain changes approach zero and almost do not vary up to the residual state after the band is cooled.

Let's consider the development of strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ at the time interval ~ 73-83 s in more details. The arc passes the middle cross section of the band at x = 300 mm at 75 s.

As it can be seen from Fig. 5-7, until the ~ 72.5 s there are no plastic strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ in any node of the cross section at x = 300 mm, however the heating source is already ~ 10 mm away from this section. This confirms the principle of the local action of the welding arc, mentioned by academician V.I. Makhnenko [10]. It also should be noted that this minimum distance of ~ 10 mm, between the arc and the cross section, depends on the power of the arc.

Development of plastic strain in all three directions along the coordinate axis starts at node 47843 with coordinate y = 30 mm on the upper heated edge. The node 47843 is located closer to the passing arc than other nodes of the cross section. From Fig. 5-7 it can be seen that linear plastic strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ in this node, occur approximately at ~ 73 s and develop until metal loss its history of temperature loading due to high heating, close to the melting point. This happens at ~ 75.5 s. Development of plastic strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ at node 47843 at the time interval ~ (73-75.5) s is shown on charts in Fig. 5-7. The most important feature at this time interval is the difference in the signs and maximum values of strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$ and $\varepsilon pzz(t)$.

There is a question about the nature of such kinetics. The difference in the signs of strain can be explained by the postulate on the incompressibility of the material under linear plastic deformation. Different values of positive strains $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ are obviously associated with different mechanical rigidity of the band in the axis directions Y and Z. It can be assumed that the band in the transverse direction (along the Y axis) has a slightly lower rigidity than in the direction of metal thickness (Z axis). Therefore, the maximum elongation strain in the transverse direction is $\varepsilon pyy(t = 75\text{ s}) = +0.00183534$, and in the direction of band thickness $\varepsilon pzz(t = 75\text{ s}) = +0.00213614$. Analyzing kinetics of temperature for the heating stage for the section at x = 300 mm (Fig. 3), it can be seen that for the node 47843, with coordinate y = 30 mm, the maximum temperature reaches the values at which metal loses its history of deformation by the temperature field. Linear plastic strains from the maximum values rapidly decrease to zero (in Fig. 5-7 we can observe line segment of small length on the abscissa axis). Maximum strains of shortening during heating $\varepsilon pxx(t) = \sim -4\cdot10^{-3}$, the sum of maximum strains $\varepsilon pyy(t)$ and $\varepsilon pzz(t)$ should have the equal value as $\varepsilon pxx(t)$, but with a positive sign, i.e. $\varepsilon pyy(t) + \varepsilon pzz(t) = \sim +4\cdot10^{-3}$, which is seen in Fig. 6 and 7.

Observing further kinetics (t = 75.5-75.75 s) of strains $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ from Fig. 5-7, it can be noted the formation of the curves with a sinusoidal shape. For strain $\varepsilon pxx(t)$ this half-wave has a negative sign again with a maximum shortening of $\sim -0.8\cdot10^{-3}$, and for $\varepsilon pyy(t)$ and $\varepsilon pzz(t)$ strains, it has a positive sign with the equal values $\sim 0.4\cdot10^{-3}$ (the postulate on the

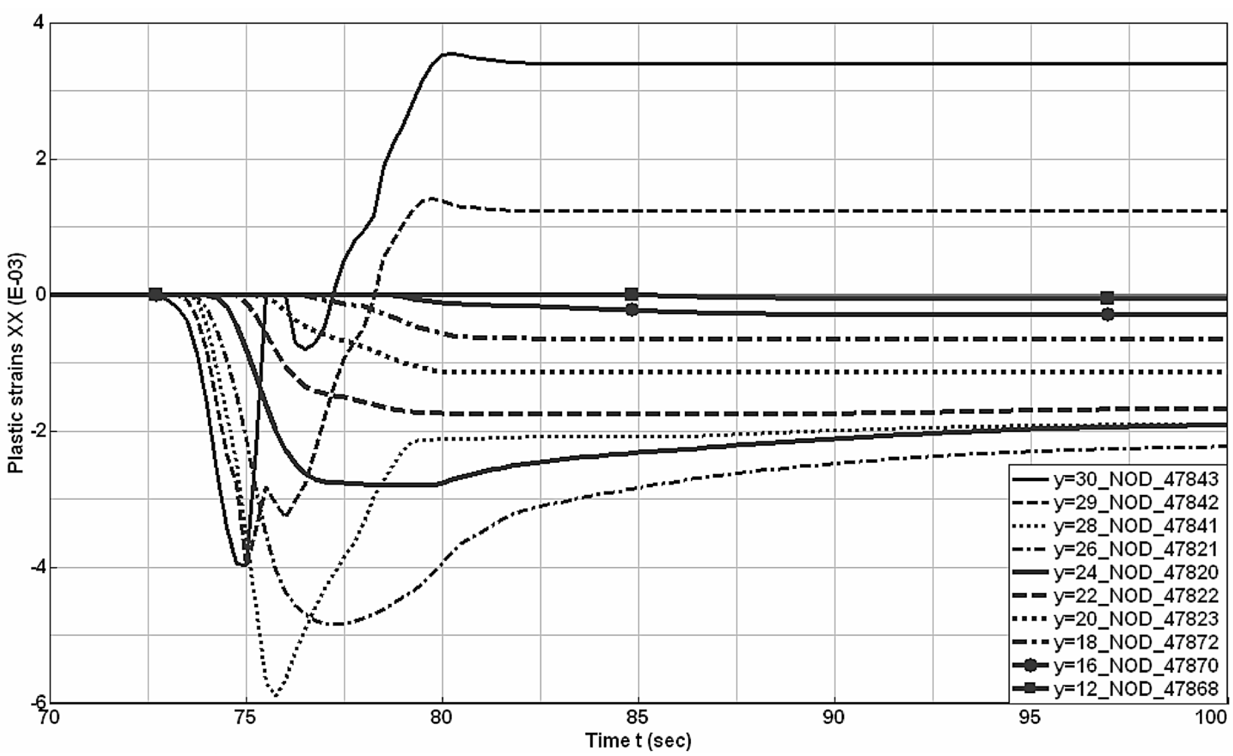

Fig. 5. Kinetics of longitudinal plastic strains $\varepsilon pxx(t)$

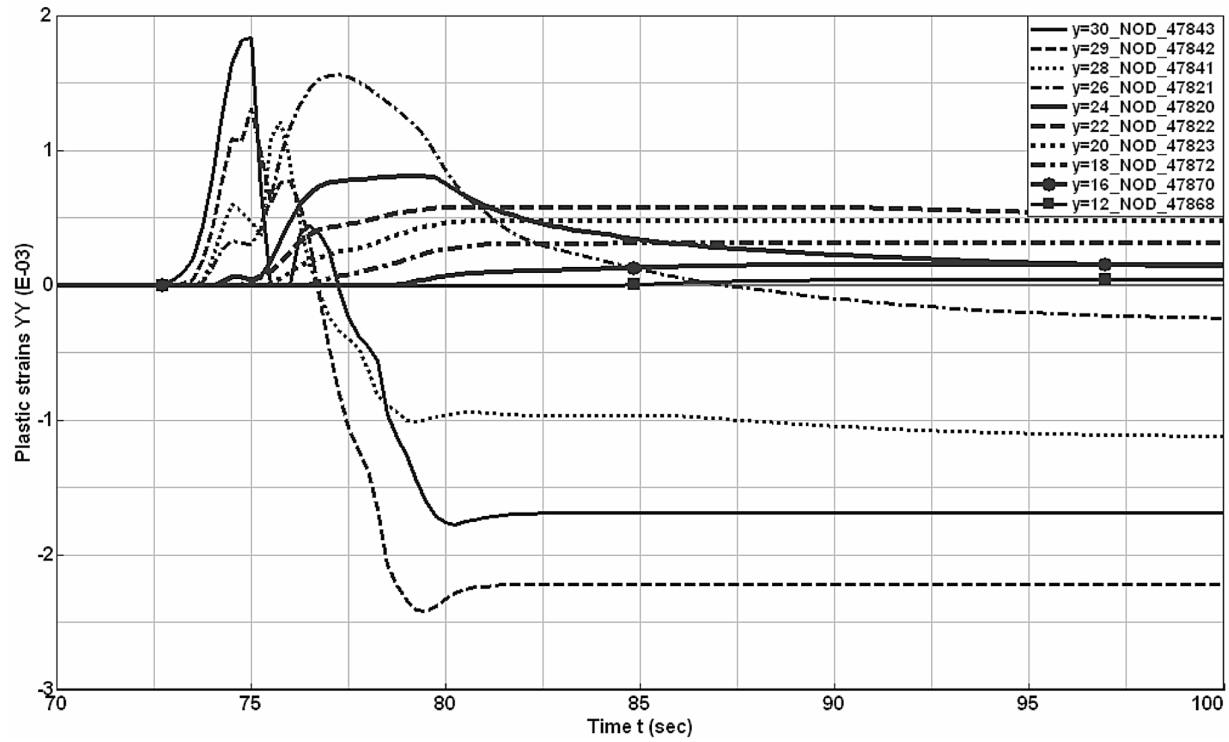

Fig. 6. Kinetics of transverse plastic strains ε*pyy*(*t*)

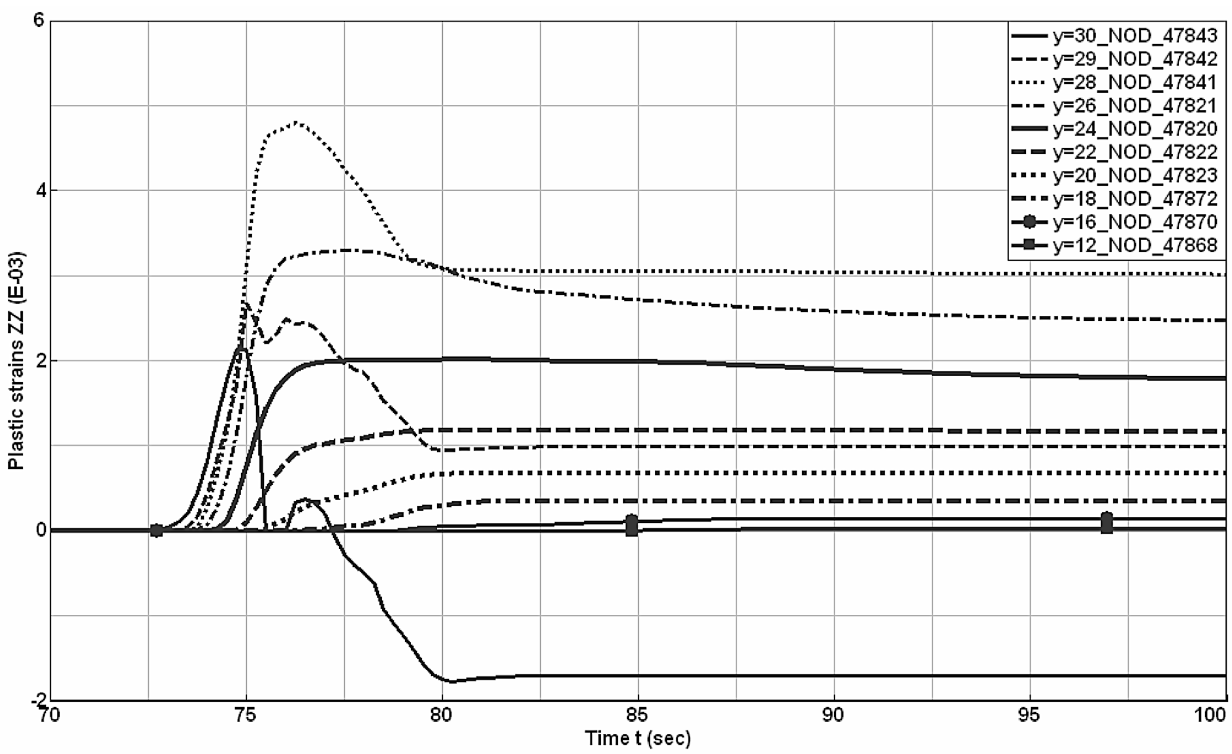

Fig. 7. Kinetics of plastic strains ε*pzz*(*t*) in *Z* axis direction

incompressibility of the material under linear plastic deformation is performed). However, there is a question about the nature of the appearance of these opposite half-waves showing on charts in Fig. 5-7, the answer to which should be obtained by considering and analyzing kinetics of temperature at the cooling stage in the band cross section in Fig. 4. This process occurs at the time interval between ~ 75.5–77.5 s. From Fig. 4, it can be seen that at this time interval, the bold solid curve for 75.5 s, at 76 s changes its position, as, if it has been moved on the place of the dashed line, which is rises higher and higher above the bold solid curve, as the distance from the heated edge increases. Basing on this, it can be concluded that during further movement of the heating source along the edge, additional amount of heat transmits into the metal of the band near the heated edge and downwards from it, which is spreading across the band width from the outgoing heat source.

From Fig. 5 it can be seen that, in general, changing of strain ε*pxx*(*t*) in time at nodes of the cross section with coordinates y = 30, 29, 28, 26 and 24 mm at the time interval ~ 73-80 s is almost equal.

Under the high heating rate of the metal by an arc plastic strains ε*pxx*(*t*) at this interval, firstly begin to increase sharply with a negative sign (shortening), and then, with the decrease in heating, the cooling process begins and the course of strain curves ε*pxx*(*t*) changes sharply with the tendency of rising up and subsequent transition through the abscissa axis to the region of positive values (elongation) for nodes of the cross section with coordinates y = 30 and 29 mm. For nodes with coordinates y = 28, 26, and 24 mm, the strain curves ε*pxx*(*t*) also rise up faster or slower, but remain negative with a gradual decrease of their absolute values to the level of the residual state after heating and complete cooling. For the remaining nodes from the considered ones with coordinates y = 22, 20, 18, 16 and 12 mm, the strain curves ε*pxx*(*t*) remain below the abscissa axis with a gradual decrease of their absolute values and a tendency for a gradual smooth transition to the residual state. Other strains ε*pyy*(*t*), ε*pzz*(*t*) (Fig. 6, 7) are changing in time in accordance with the postulate on the incompressibility of the material under linear plastic deformation. Of considerable interest is the changes of the curve of strain distribution over the cross section of the band ε*pxx*(*S,t*), ε*pyy*(*S,t*), ε*pzz*(*S,t*) depending on the distance *S* from the heated edge at different times of its heating. Position of the heating source on the edge of the band is determined by the time *t* of the heating process. Curves of strain distribution ε*pxx*(*S,t*), ε*pyy*(*S,t*) and ε*pzz*(*S,t*) are presented in Fig. 8-10.

For 10 nodes of the section with coordinates y = 30, 29, 28, 26, 24, 22, 20, 18, 16 and 12 mm each of these Figures shows 11 curves for 11 time moments *t*. In the chart legends these curves are arranged from top to bottom in accordance with the notation adopted for them. Charts of the strain distribution ε*pxx*(*t*) over cross section that are shown in Fig. 8 originate from 74 s, for which the strain curve is shown with a triangular marker. Maximum strain of shortening takes place on the edge of the band and is equal to ~ $-1.6{\cdot}10^{-3}$, plasticity zone at the time *t* = 74 s speads 6-7 mm downwards from the heated edge over the width of the band, while the arc is in 4 mm before the middle cross section.

In Fig. 8, for other time moments *t* = 74.25; 74.50; 74.75 and 75 s, charts of the strain distribution ε*pxx*(*S,t*) over the cross section locates below. At 75 s, the arc on the edge of the band reaches the section at

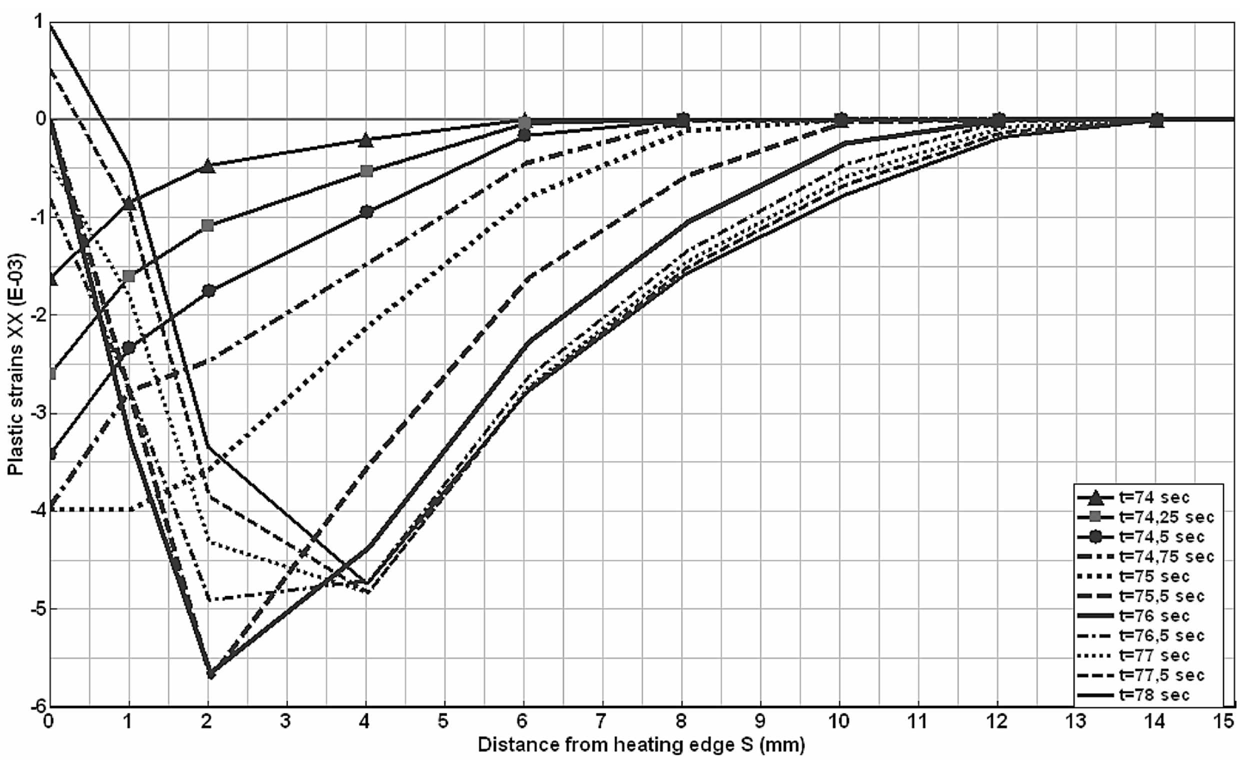

Fig. 8. Distribution of plastic strains ε*pxx*(*S,t*) in the section at x = 300 mm depending on distance *S* and the moment of the edge heating *t* = 74-78 s

x = 300 mm, at this moment the chart of strain distribution $\varepsilon pxx(S,t)$ is shown by a bold dotted line. For a node on the edge of the band the maximum value of $\varepsilon pxx(S,t)$ is ~ $-4{\cdot}10^{-3}$, at the time t = 75 s width of the plasticity zone in downward direction from the heated edge of the band is ~ 10 mm, the arc locates just above the section at x = 300 mm. During the process of subsequent heating of the edge, the arc crosses the cross section at x = 300 mm and moves further along the edge of the band.

For all charts $\varepsilon pxx(S,t)$ on the heated edge at the time moments t = 75.5; 76; 76.5; 77; 77.5 and 78 s negative values of $\varepsilon pxx(S,t)$ decrease and even pass into the region of positive values, as for example, charts for the time moments t = 77.5 and 78 s. The plasticity zone extends downwards from the heated edge of the band up to ~ 14 mm, the maximum values of the longitudinal shortening reach ~ $-5.54{\cdot}10^{-3}$ at 78 s, when the arc has already moved away from the cross section by 12 mm.

For time moments t = 77.5 and 78 s, the charts of $\varepsilon pxx(S,t)$ in the descending part are almost merge, which means that, with increasing time t, the process of further expansion of the zone of plastic strains has been stopped, however at the area close to the heated edge, a decreasing of strain values of shortening will continue for some time as the band cools.

Charts of strain distributions $\varepsilon pyy(S,t)$ and $\varepsilon pzz(S,t)$ over the cross section (Fig. 9, 10) are fully satisfy the postulate on material incompressibility under linear plastic deformation and are consistent with the similar strain distribution $\varepsilon pxx(S,t)$ shown in Fig. 8.

When the arc approaches the cross section at x = 300 mm, the distribution of plastic strain $\varepsilon pyy(S,t)$ will be considered from 74 to 75 s, within the time interval of 0.25 s. This heating stage includes 5 curves shown in Fig. 9. With the increase in time t, charts gradually rise up and reaching maximum values of $\varepsilon pyy(S,t)$ on the heated edge (the distance from the edge along the abscissa axis is zero). Starting from 75 s, the mesh node of the model, on the edge of the band, gradually transits into a state close to melting, in which all entire history of metal loading disappears, the SSS at the node is zeroed until the 76 s, what can be seen from Fig. 9.

In Fig. 9 bold dashed and solid curves originates from zero value of transverse plastic strain $\varepsilon pyy(S,t)$, which is plotted along the ordinate axis. At first sight, it may seems strange that the transverse plastic strain at this stage at the region of the heated edge has a positive sign. However, everything in this area is determined by the sign and magnitude of plastic strain $\varepsilon pxx(S,t)$ (Fig. 8). From Fig. 8 it can be seen that strain $\varepsilon pxx(S,t)$ in this zone has a negative sign, i.e., shortening of the significant value. This area is heated by the arc and if it was not connected with the band, it had been extended according to the temperature increase. However, the heated zone near the edge is surrounded by a cold metal, and this resembles the development of thermo-deformation processes in a rod which is rigidly clamped at two ends, in which, as it is known [3-7], plastic strain of shortening occurs (negative sign).

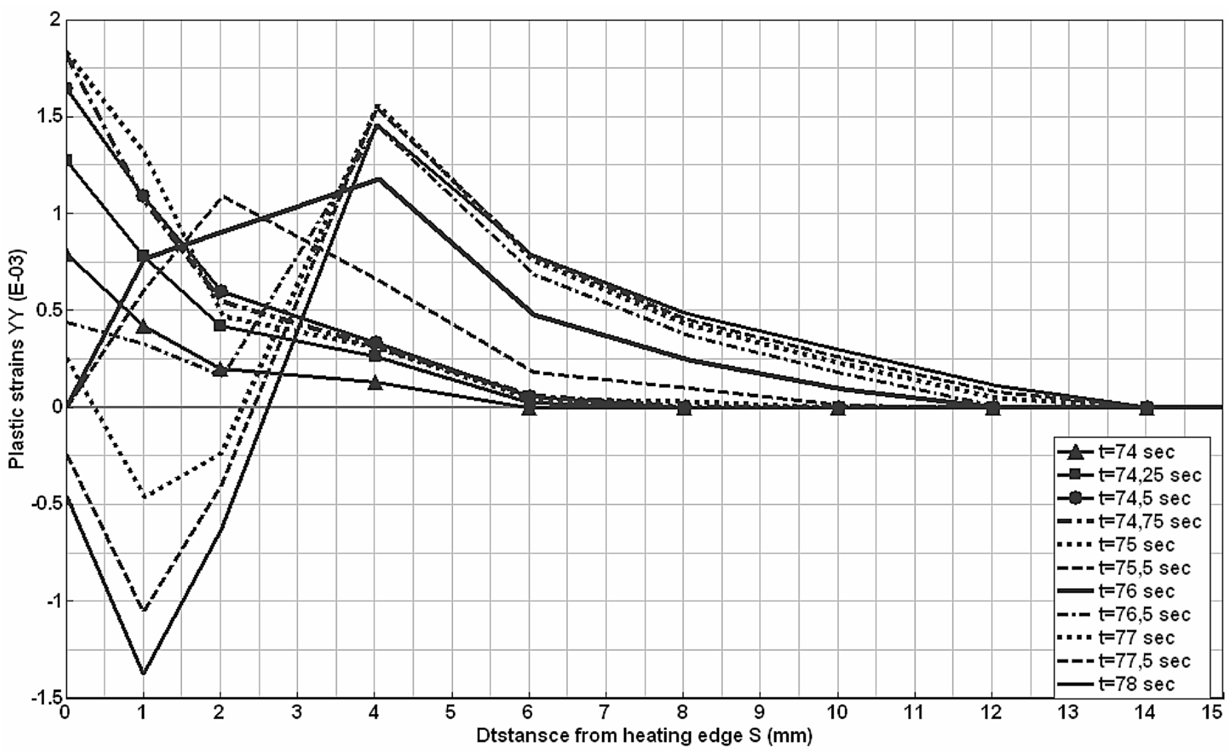

Fig. 9. Distribution of plastic strains $\varepsilon pyy(S,t)$ in the section at x = 300 mm depending on distance S and the moment of the edge heating t = 74-78 s

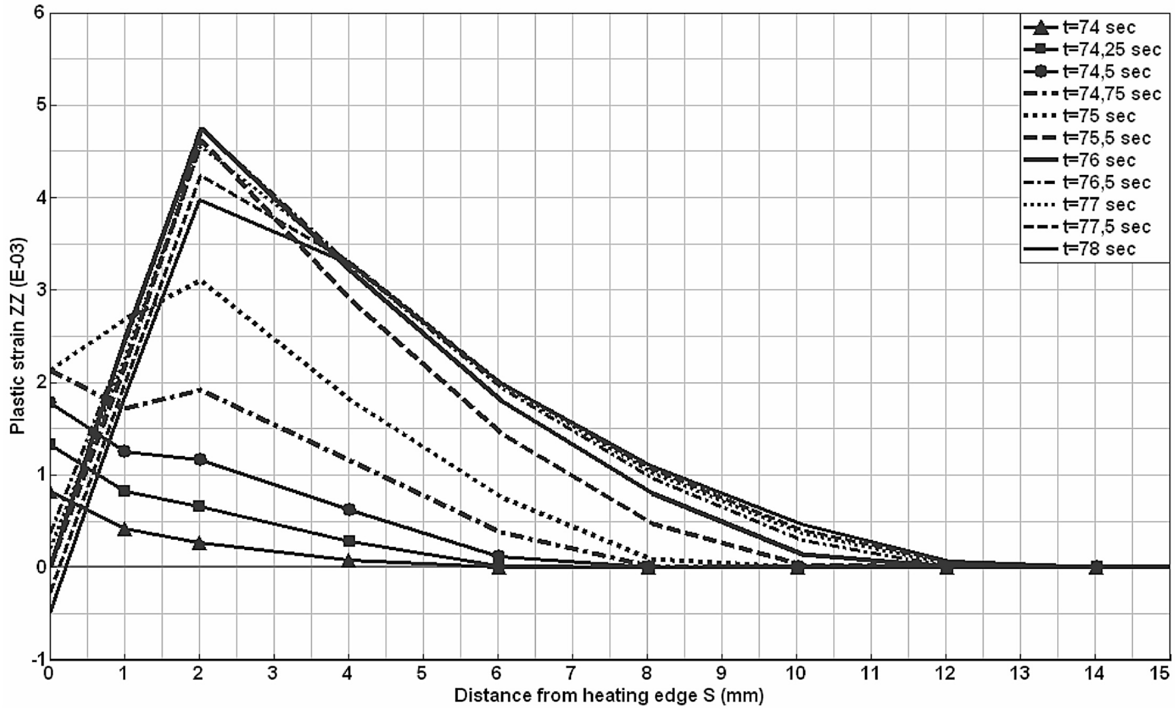

Fig. 10. The distribution of plastic strain $\varepsilon pzz(S,t)$ in the section at x = 300 mm depending on distance S and the time of the edge heating t = 74-78 s

Thus, if a cubic element of a metal is plastically compressed along the X axis (longitudinal direction), then, in accordance with the postulate of the material incompressibility under linear plastic deformation, sum of plastic strains in the directions of the coordinate axes should be zero. Therefore, in order to compensate significant negative strain $\varepsilon pxx(S,t)$, it is necessary that in the transverse direction Y and in the band thickness direction Z, plastic strains $\varepsilon pyy(S,t)$ and $\varepsilon pzz(S,t)$ have a positive sign, which can be seen in Fig. 9, 10.

How the formation of plastic elongation during heating can be explained? We assume that it is also necessary to take into account the mechanical rigidity of the heated structure. If the mechanical rigidity of the band in the X and Y directions was the same, then strains $\varepsilon pyy(S,t)$, $\varepsilon pzz(S,t)$ would be positive and of the equal values, same as in the example of concentrated heating of a metal sheet with relatively small thickness, but with considerable dimensions in the plane of the sheet (for example, in resistance spot welding or when the sheet is heated by a non-moving flame source). In the center of the heating zone, radial plastic strains are equal in all directions and are of negative values (shortening), while plastic strain in the direction of the sheet thickness is of positive values (elongation), i.e. thickness of the sheet in the zone of concentrated heating increases (the sheet "swells"). The sum of all plastic strains in three mutually perpendicular directions is zero.

In our case, we see that strain $\varepsilon pzz(S,t)$ is approximately 5 times greater than strain $\varepsilon pyy(S,t)$. This indicates that, due to the small band thickness in Z direction, it has low rigidity and therefore, in the zone of heated edge, its thickness increases (the band edge "swells"). Consequently, the band in this direction is plastically elongated. In the transverse direction (along the Y axis), the rigidity of the band is greater, and strain $\varepsilon pyy(S,t)$ is lower. When the heating source moves away from the cross section at x = 300 mm along the heated edge, the location of the charts in Fig. 6 and 7 is determined by the rate of inflow (closer to the heated edge) or outflow (farther from the heated edge) heat to the area under consideration.

Next, consider kinetics of shear plastic strains $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ in the band during heating and cooling of the longitudinal edge by the moving welding arc (Fig. 11-13). From these figures, it can be seen that only shear strain $\gamma pxy(t)$ reaches great values ~ $-(4.0\text{-}9.0)\cdot 10^{-3}$ for nodes of the cross section with coordinates y = 29, 28 and 26 mm located within 4 mm from the heated edge. Other shear strains (Fig. 12, 13) are in range from ~ $-0.5\cdot 10^{-3}$ to $+1.5\cdot 10^{-3}$ for $\gamma pyz(t)$ and from $-0.25\cdot 10^{-3}$ to $+1.5\cdot 10^{-3}$ for $\gamma pxz(t)$.

It is conveniently consider the distribution of shear plastic strains $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ in in cross section of the band at x = 300 mm for mesh nodes depending on the distance S from the heated edge, as shown in Fig. 14-16.

Each chart corresponds to a specific time of heating and cooling process of the band. In Fig. 14-16 the top 5 charts in the legends are related to the time interval 74-75 s, correspond to the maximum heating process of the most extreme upper node of the section at x = 300 mm on

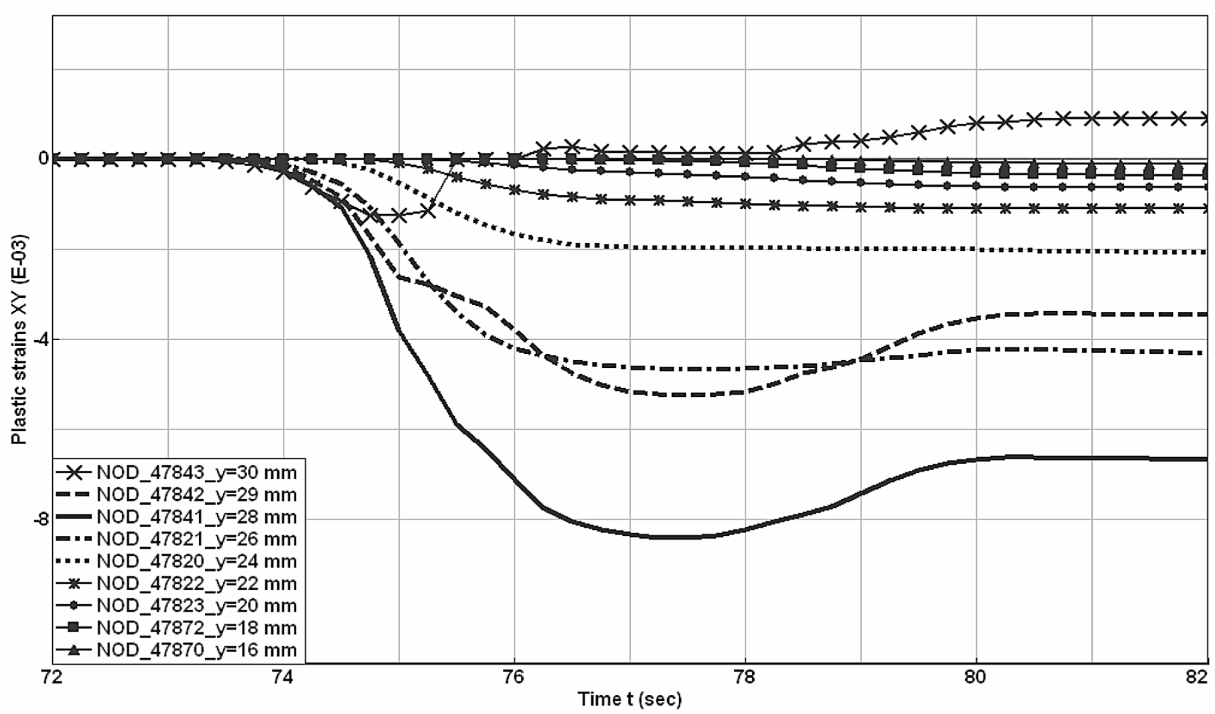

Fig. 11. Kinetics of shear plastic strains $\gamma pxy(t)$ in the mesh nodes for section at x = 300 mm at time interval t = 72-82 s

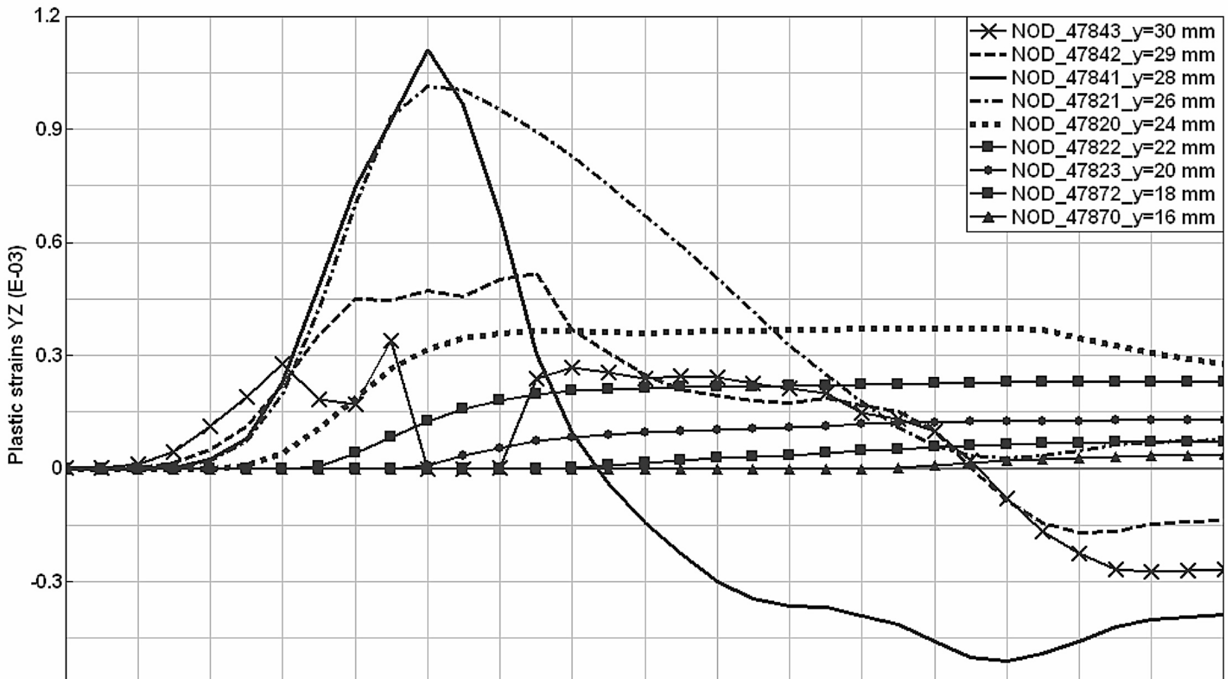

Fig. 12. Kinetics of shear plastic strains $\gamma pyz(t)$ in the mesh nodes for section at x = 300 mm at time interval t = 73-81 s

the edge of the band, when the metal is not melted yet. Later, at the time interval 75.25-75.75 s, the node on the edge of the band corresponds in its physical properties to the molten metal, but retains the properties of a solid deformable continuum. At the same time, all previously acquired parameters of the SSS are zeroed, the charts in Fig. 14-16 corresponding to this time interval t, originate at zero value of the coordinate system (zero values of shear plastic strains $\gamma pxy(S,t)$, $\gamma pyz(S,t)$, $\gamma pxz(S,t)$). The last two charts for time moments 76.5 and 77 s in Fig. 14 correspond to the initial cooling stage of the considered node at the edge. For subsequent time values of t, charts

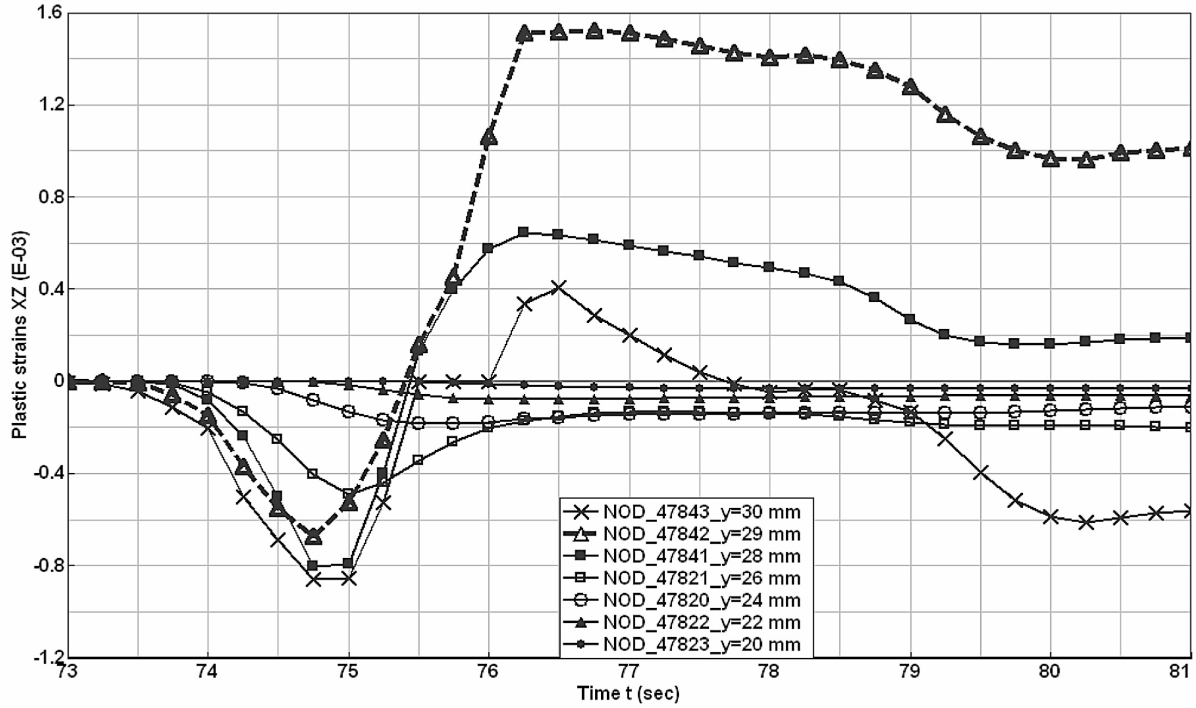

Fig.13. Kinetics of shear plastic strains $\gamma pxz(t)$ in the mesh nodes for section at x = 300 mm at time interval t = 73-81 s

in Fig. 14 almost merge and the distribution of plastic shear strains $\gamma pxy(S,t)$ for the section at x = 300 mm remains unchanged until the end of cooling, the width of the plastic zone over the section reaches ~ 14 mm. For shear strains $\gamma pyz(S,t)$ and $\gamma pxz(S,t)$, the stages of molten metal in Fig. 15 and 16 correspond to time moments 75.5 and 76 s. The cooling process starts at 76.5 s and continues up to 78 s for the charts shown in Fig. 15 and 16. The width of the zone of plastic strains $\gamma pyz(S,t)$, $\gamma pxz(S,t)$ remains unchanged ~ 14 mm. Residual shear

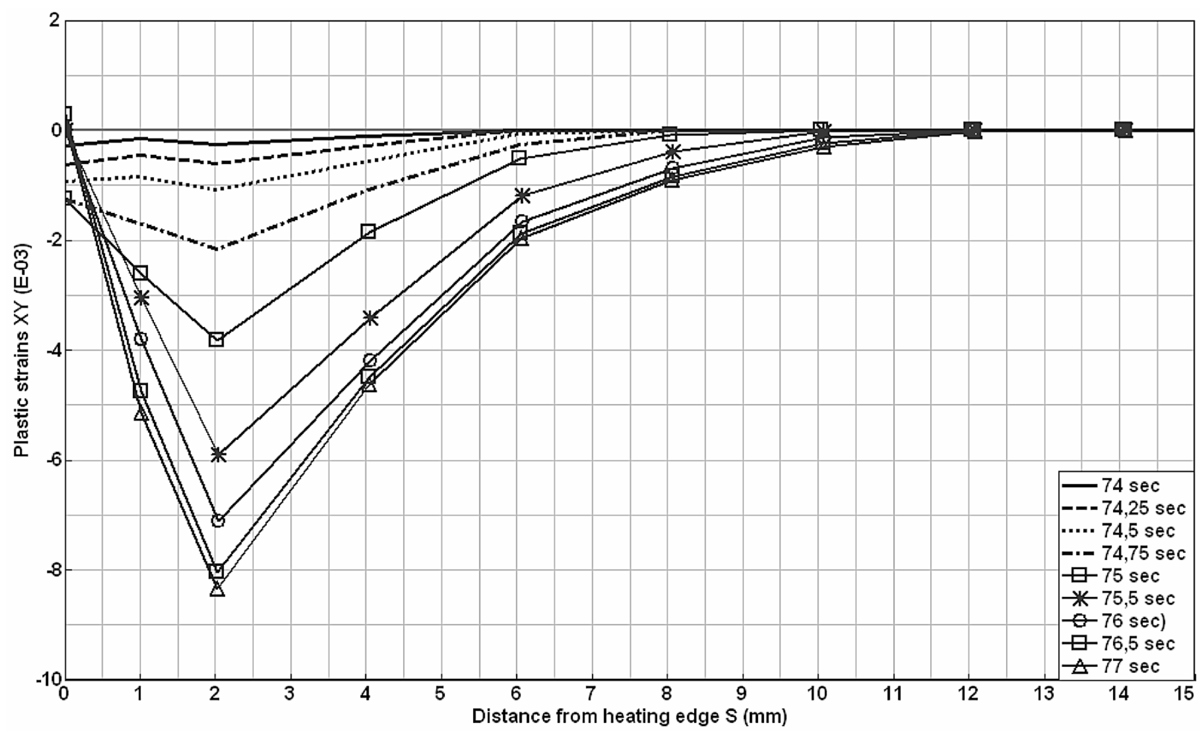

Fig.14. Shear plastic strains $\gamma pxy(S,t)$ in the section at x = 300 mm depending on the distance S from the heated edge and the heating time t = 74-77 s

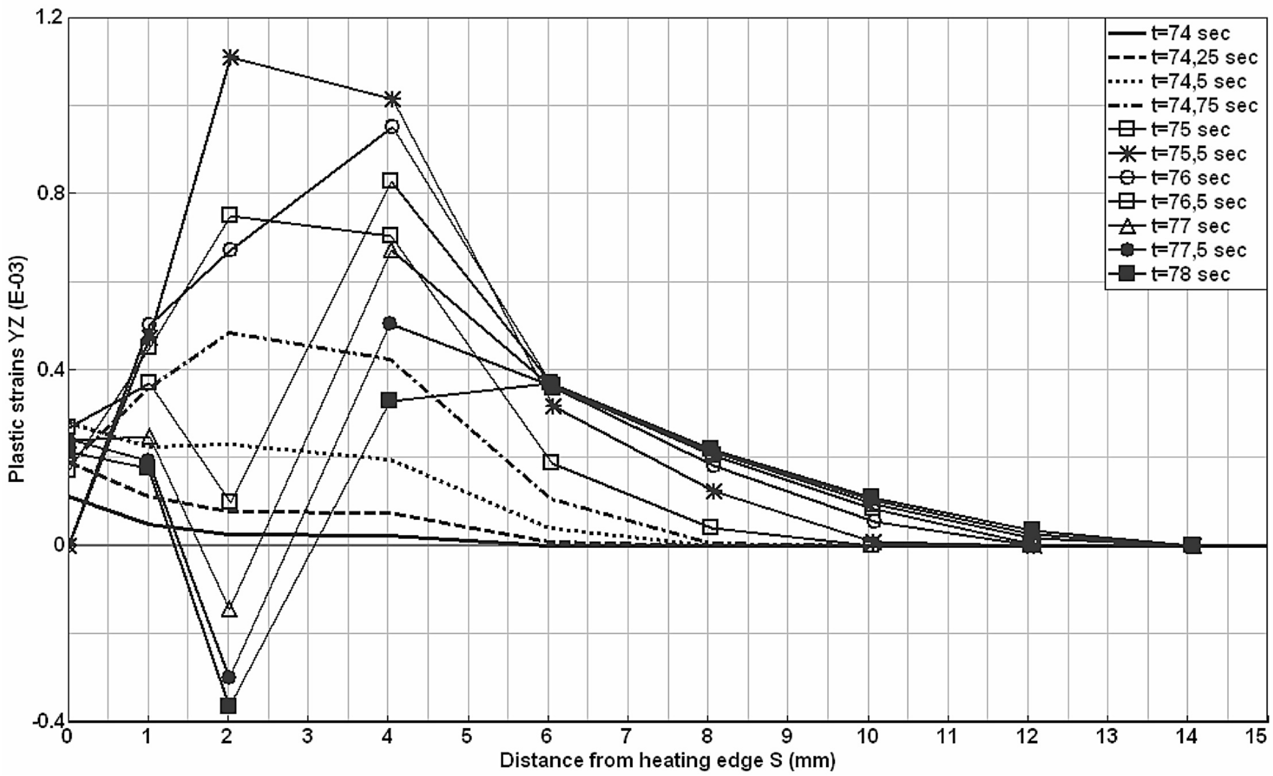

Fig.15. Shear plastic strains *γpyz*(*S*,*t*) in the section at x = 300 mm depending on the distance S from the heated edge and the heating time t = 74-78 s

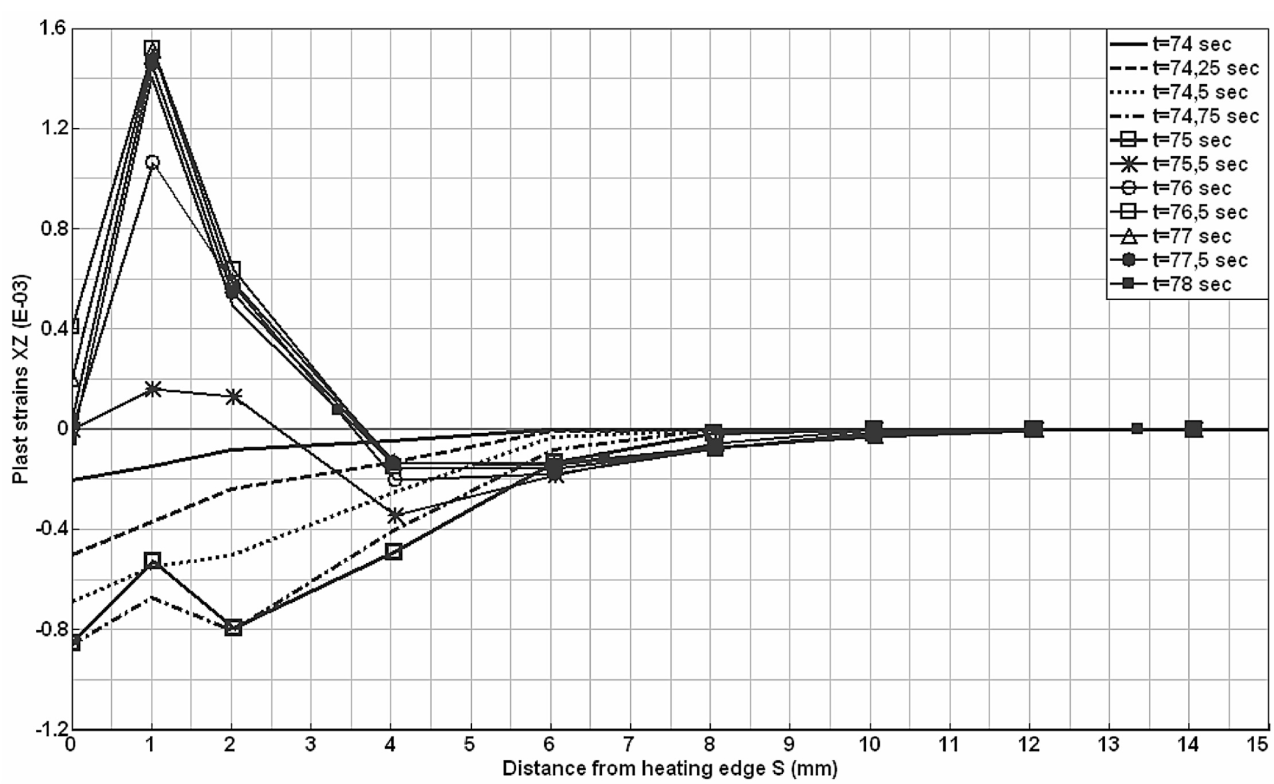

Fig.16. Shear plastic strains *γpxz*(*S*,*t*) in the section at x = 300 mm depending on the distance S from the heated edge and the heating time t = 74-78 s

plastic strains create in the band insignificant residual shear stresses within: τxy = ~ (–25...+7) MPa, τyz = ~ (–15... + 17) MPa, τxz = ~ (–3...+15) MPa.

Conclusions

1. The finite element method has been used to solve a coupled temperature elasto-plastic problem of kinetics of temperature during the heating and cooling stages, as well as plastic linear and shear strains, at the nodes of the cross section of the heating zone of the band mesh model with dimensions of 600×60×4 mm made from 08пс steel during heating of its longitudinal edge by a moving welding source.

2. Analysis of the obtained calculated results showed that the trends of kinetics changes of plastic strains in the heated zone of the band from the heated edge are determined by the directionality of the heat fluxes which are formed in this zone behind the moving heating source along the longitudinal edge.

3. It has been established that the duration of the time interval of significant changes in kinetics of plastic linear and shear strains in the band middle (x = 60...540 mm) cross-sections is ~ 10 s for the heating mode that has been used in this paper for the longitudinal edge of the band. The time interval starts at the node of the cross section on the heated edge with coordinates (y = 30 mm, z = 2 mm), in 2 seconds before the heating source approaches the section (8 mm before the cross section). The end of noticeable changes of kinetics occurs in 8 s after the heating source passes the cross-section (32 mm after the cross section).

4. Comparing of the temperature distribution curves across the band cross section for a final time moment 75.5 s of the heating stage of the node on the band edge in the middle cross section (Fig.3, bold solid curve) and the curve after 0.25 s (75.75 s) from the beginning of the node cooling stage at the edge (Fig.4, bold dashed curve), it has been established that the band area up to 15 mm wide from the heated edge receives a significant amount of heat due, since it transmitted to this area from the highly heated zone. This heat has significant negative affect on kinetics of longitudinal plastic strains εpxx, which are determine the shrinkage force, and increases the bending moment from the shrinkage force, respectively, and finally the residual flexure of the band axis line. The heat transmitted to this zone of the band slows down the cooling rate of the nodes from the heated edge side and slows down or completely stops rise of the εpxx curves for the corresponding nodes of the cross-section from the region of negative values (shortening area) to the region of positive values (elongation area), which is necessary to strive for to reduce the relative volume of longitudinal plastic shortening in order to reduce the amount of residual flexure of the band.

5. Thus, taking into account p. 4 of the conclusions, we can propose, in our opinion, a reasonable idea of the technological solution that allows to reduce the residual flexure of the band significantly when its longitudinal edge is heated by the moving welding arc, which is technically based on any of the known or new cooling technologies of the band from the lateral sides behind the edge heating source at a distance of 10 to 20 mm from it and 5 mm below the heating edge. Such concomitant cooling of the band will make it possible to lower the distribution curve of the temperature in the active cooling zone over the cross section of the band at the initial cooling stage (~ 76 s, bold dashed curve in Fig. 4) by 130 °C. All parameters of the cooling devices can be calculated.

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КИНЕТИКА ТЕМПЕРАТУРЫ И ПЛАСТИЧЕСКИХ ДЕФОРМАЦИЙ ПРИ НАГРЕВЕ ДВИЖУЩИМСЯ СВАРОЧНЫМ ИСТОЧНИКОМ ТЕПЛА ПРОДОЛЬНОЙ КРОМКИ СТАЛЬНОЙ ПОЛОСЫ

В работе представлены результаты конечно-элементного моделирования кинетики температуры, линейных $\varepsilon pxx(t)$, $\varepsilon pyy(t)$, $\varepsilon pzz(t)$ и сдвиговых $\gamma pxy(t)$, $\gamma pyz(t)$, $\gamma pxz(t)$ пластических деформаций в полосе 600×60×4 мм из стали 08пс при нагреве ее по осевой линии плоскости продольной кромки сварочной дугой в аргоне (TIG-процесс сварки).

Цель работы заключалась в поиске идеи технологического решения для уменьшения остаточного прогиба осевой линии полосы, совмещенного с этапом выполнения основного технологического процесса нагрева стальной полосы. [dx.doi.org/10.29010/084.7]

Ключевые слова: *стальная полоса; подвижной источник нагрева J. Goldak; кинетика температуры и пластических деформаций.*

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