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Research Article

The Finite Element Modulation of Thermostressed State of Coating Formation at Electric Contact Surfacing of "Shaft" Type Parts

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The finite element modulation of forming of coating at electric contact surfacing is provided. This model considers distribution of thermal properties and geometric parameters along the thermal deformation zone during the process of electric contact surfacing by tapes. It is found that the change of the value of the speed asymmetry factor leads to increasing of the friction coefficient in the zone of surfacing which is caused by the increasing of the tangential contact stresses in the zone of contact of the electrode tape with the surface of the part. This leads to the forming of the coating with higher adhesion strength, and thereby the higher quality of the restored part under the lower operating regimes such as current pulse, force of the roller electrode, and duration of the current pulse is achieved. Mentioned above allows to decrease the thermal influence on the structure of the material.

1. Introduction

In the case of electrocontact surfacing, the bond between the welded and the base metals is formed by their joint compression as a result of heating by the transmitted electric current under conditions of the welded metal plastic deformation. In this connection, the main advantage of the electrocontact surfacing in comparison with the arc surfacing methods is a bond between the welded and the base metals without melting them. This helps to prevent mixing of the welded and the base metals, to reduce the thermal influence zone size, and to avoid defects in the cast structure [1–3]. The electrocontact surfacing method is characterized by high productivity and low energy consumption of coatings [4]; minimum zone of thermal influence on a part; and absence of necessity to use protective atmosphere and absence of radiation and gas evolution. The process of electrocontact surfacing is characterized by short-term high-speed heating (800–1000°/sec) of welded material and base metal to temperatures of 1400–1600°C and the force action of roller electrodes. Heating occurs by passing a pulsed current through the welded material, which is under pressure from the deformation force between the base metal and the roller electrode. Electrocontact surfacing refers to the number of processes with pronounced force and temperature activation. The magnitude of the force action is by 2-3 times higher than in the case of the centrifugal induction and vibrational and other technological options for obtaining coatings. Electrocontact surfacing occurs under the action of two activating factors: forces on the roller electrode and current strength. This allows significantly speeding up the coating on the surface of parts [5–7]. At the same time, the physical and mechanical properties of the layer obtained on the surface of the restored product (wear resistance, hardness, porosity, etc.) depend on the technological parameters of the process, which must be selected taking into account the influence of activating factors such as force and temperature activation. Considering the short-term course of the electrocontact surfacing process, there are certain difficulties in predicting the quality of the obtained coating and its compliance with the main operational properties. Therefore, there is a necessity to use a mathematical apparatus for analytical modeling of electrocontact surfacing in order to optimize the main parameters of the process to obtain a coating that best meets the specified requirements.

Regardless of the welded metal type (metal tape, wire, powder materials, or their compositions) [8, 9], the nature of the bond formation with the base metal remains unchanged, which is explained by the generality of the main regularities of the welded bond formation in the metals surfacing by pressure [10–12]. Dubrovskiy and Bulychev [13] developed a theoretical model of the formation of the welding areas of homogeneous metals during electrocontact welding. Dependences are obtained for the calculation of the size of the welding areas under electrocontact welding on different modes. It has been established that, with the electrocontact welding of iron-based alloys, the formation of welding areas with high bonding strength is possible when heated to critical temperatures [13].

It is noted in the work [14] that, in the case of wire electrocontact surfacing, its plastic deformation leads to a shift in the welded metal volumes on the surface of the part both in the radial (across the welded metal seam) and in the axial (along the welded metal seam) directions. According to the work [14], experimental data indicate an increase in the strength of the bond between the deposited wire and the part with increasing axial deformation. However, the axial deformation in this work was controlled by changing the temperature parameters of the surfacing conditions and this complicates the assessment of the deformation processes impact on the increase in strength of the resulting welded layer. Bulychev and Zezyulya [15] proposed a mathematical model of the process of forming a layer on the surface of cylindrical parts during electrocontact surfacing with wire. The study is aimed at solving the problem of increasing the adhesion strength between the wire being deposited and the part without increasing the heat input and, accordingly, with minimizing the thermal effect on the part. This problem, according to [15], can be solved by developing methods for controlling the axial deformation of the wire without changing the strength and duration of the surfacing current pulses. According to the mathematical model of the electrocontact surfacing process presented in the work [15], the values of the roller electrode rotation delay factor should be selected in the range 0.54–0.64. The results of the experimental studies given in the work [15] confirm the possibility of a significant increase in the strength of the adhesion of the wire to the part by increasing only the axial strain of the wire. Because of this, the wire axial deformation can be represented as one more controlling parameter of the surfacing conditions. However, in order to apply the welded method with delayed rollers-electrodes in practice, it is necessary to develop a method of effective control of the deposited wire axial deformation.

In the work [16], there is a mathematical model of a sintered tape formation by reinforced metal lath for increasing mechanical characteristics using the method of electrocontact surfacing. The normal contact stresses in the center of deformation are determined. It is noted that the proposed method for calculating the sintering zone during the manufacture of reinforced powder tape can also be used to estimate the parameters of the electrocontact surfacing process.

In the case of electrocontact surfacing to obtain a quality weld joint, it is important to know the nature of the heat distribution in the joint zone of the base and the welded metal. The main difficulty in surfacing the working layers is obtaining the required temperature distribution over the whole contact area due to uncontrolled and uneven surfacing current density in various areas of electrical contact, with different conditions for heat removal.

Gulakov et al.[17] show the solution of the problem by obtaining a data array with their subsequent processing and finding the optimal parameters for the surfacing regime. However, to optimize the process parameters, dozens of experiments must be carried out. It is a labor-intensive process and takes a large number of machine resources. In consideration of the electrocontact surfacing real process short duration, making a fraction of a second, it is difficult to produce such a volume of calculations in real time. Lavrentik and Pavlova [18] proposed a simplified calculation model for estimating the influence of factors on the heat distribution over the weld joint contact area according to various criteria. Mathematical description of temperature distribution allows us to simplify the modeling, building, and predicting real dependencies processes for various parameters of a real experiment. To describe the data, the regression equations were obtained on the basis of the density function of the normal probability distribution for one-dimensional and two-dimensional models of temperature distribution in the contact zone. Statistical analysis allows determining the influence degree of a factor on the temperature distribution and, depending on this, optimising the process parameters to obtain a qualitative weld joint. It was established in the work [19] that gravity surfacing is performed with tangential force, which leads to the tangential stress appearance in the contact zone of the joined metals that requires taking this factor into account in modeling the electrocontact surfacing process. In the works [20, 21], the effect of strain rate on the grain size of rolled steel was simulated and the effect of an energy pulse on the structure of the coating material was also investigated. However, the technology proposed in the works under consideration involves the modification of the surface layers without coating, which does not quite coincide with the purpose of this study.

With the development of coating technologies by the electrocontact method, the empirical approaches in the choice of coating design and process schemes ran their course. This provides analysis of the electrode material stress-strain state in the process of electrocontact surfacing, taking into account the real nature distribution of the physicomechanical properties under the influence of thermal and mechanical loads at the stage of designing the technological process. In view of the physicochemical processes complexity occurring during the coating by electrocontact methods, the existing analytical dependencies do not provide an opportunity for comprehensive study of the welded layer formation. This makes it necessary to use finite element simulation methods for analyzing the distribution of energy-force parameters and thermal fields over the cross-sectional layer for the purpose of optimizing the modes of electrocontact surfacing. In the work [22], based on a theoretical analysis of the electrocontact surfacing by tapes conditions using the finite difference method, the influence of the kinematic asymmetry coefficient magnitude on the change in the local energy-force characteristics of the process was established. The kinematic asymmetry coefficient is determined by the ratio of the linear velocities on the roller electrode and the remanufactured part. It is shown that, with the kinematic asymmetry coefficient increase to 1.015, the amount of tangential contact stresses in the surfacing zone increases too, which must be taken into account when designing the technological process. On the basis of experimental studies of the electrocontact surfacing by tapes, the adequacy of the developed finite difference model was confirmed. According to the results of the experimental verification, the error in calculating the force on the roller electrode and the current impulse strength does not exceed 10%. On the basis of electrocontact surfacing by tapes technological modes automated design, the tasks of ensuring the necessary geometric parameters of the coating are solved. However, in view of the thermal field distribution experimental verification complexity and also taking into account the one dimensionality of the proposed mathematical model, it is necessary to develop a two-dimensional model for more accurate account of all factors and for obtaining more reliable picture of the stress-strain and thermal state. The construction of such two-dimensional models should be performed by the finite element method to make the most efficient use of them.

2. Prime Novelty Statement

The formation of coating at electric contact surfacing of "shaft" type parts is investigated.

The effect of the kinematic asymmetry coefficient of the electrocontact surfacing, which is determined by the ratio of the velocities of the roller electrode and the cylindrical part, on the change in the thermal and energy-force local characteristics of the process is investigated. The optimum value of the kinematic asymmetry coefficient is established, which makes it possible to increase the tangential contact stresses in the contact zone of the tape with the surface of the part. In the zone of contact of the tape with the roller electrode, tangential contact stresses remain unchanged, which must be taken into account during the development of the technological process.

On the basis of finite element modeling, it is established that, when the kinematic asymmetry of the electrocontact surfacing process with the value of the coefficient $K_v = 1.015$ is established, the bond strength of the reduced samples increases by 24.3–26.8%.

3. Theoretical Studies

For the purpose of carrying out the research, the changes in the local characteristics of the electrocontact surfacing process by tapes of cylindrical parts, taking into account the actual conditions of the process, and also for testing the adequacy of the proposed mathematical model, the finite element modulation of the process was carried out. Finite element modulation of the electrocontact surfacing by tapes of cylindrical parts is realized on the basis of the Abaqus software complex using the Abaqus/Standard solver and provides a joint solution of the electrical heating and plastic deformation problems, including the surfacing of the electrode tape to a cylindrical surface. In the modulation, the design model, shown in Figure 1(a), was used.

This model, in order to simplify and reduce the amount of calculations, taking into account the plane symmetry XY (Figure 1), represents the half of the task. It consists of deformable element, modeling the electrode tape, two absolutely rigid, nondeformable bodies modeling the part being restored, and roller electrode. Besides, to ensure the clamping of the roller electrode with the force necessary for carrying out the electrocontact surfacing, the elastic element is included in the model. The contact interaction between the roller electrode 3 and the electrode tape 1 is described by Coulomb's Friction Law through the coefficient of friction, represented in the temperature function in accordance with the data of Grudev [23].

In the zone of contact interaction between the cylindrical surface of the part and the electrode tape, in order to simulate the adhesion process, the "closing" of the contacted surface of the tape with the part is additionally realized. Actually the process simulation is realized in several stages:

(i) First, the roller electrode is pressed against the tape along the upper line of the front end face, which is realized by shifting the upper fixing point of the elastic element 4 by an amount capable of providing the required pressing force of the roller electrode.

(ii) Next, after ensuring the pressing force, the part 2 and the roller electrode 3 are rotated, and the electric heating of the electrode tape is initiated.

Taking into account the impulse (periodic) nature of the electric load application and the relatively short time of influence, the electric current to the tape is implemented on the upper area of the surface, represented in the diagram (Figure 2) in the form of grid with the length that the tape passes during the period of the electric load. It includes a heating cycle up to the surfacing temperature and a pause (disconnection of the electric current). The electric potential is applied to the lower surface, which is shown in Figure 2 in the form of points along the surface area of the tape of the same length. The heat removal from the tape surface is realized on its surface, excluding the front and back end surface of the tape, the surface passing through the symmetry plane, and also the upper surface to which the electric load is applied. The roller electrode in the process of electrocontact surfacing is forcedly cooled by the water, which is supplied through the cooling channel. After the first period of heating the tape (Figure 2), the transition to the next section of the same length occurs, in order to carry out further electrical heating of the tape.

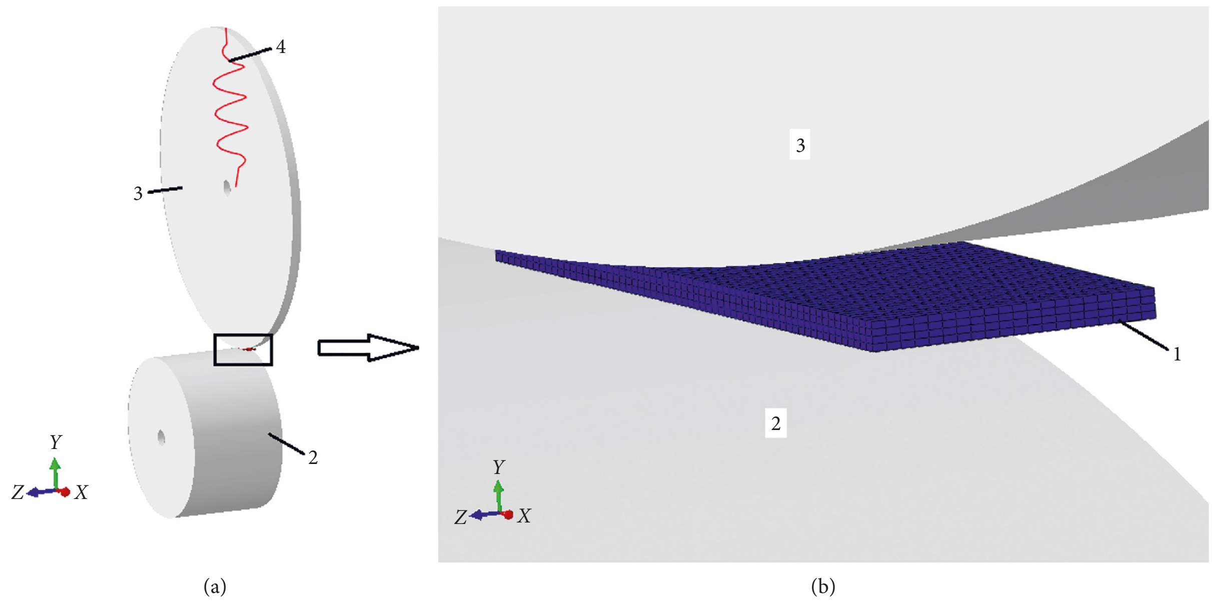

Figure 1: Design model of the finite element modulation of the electrocontact surfacing of cylindrical parts by the tape. 1, electrode tape; 2, cylindrical part; 3, roller electrode; 4, elastic element simulating the clamping force of the roller electrode.

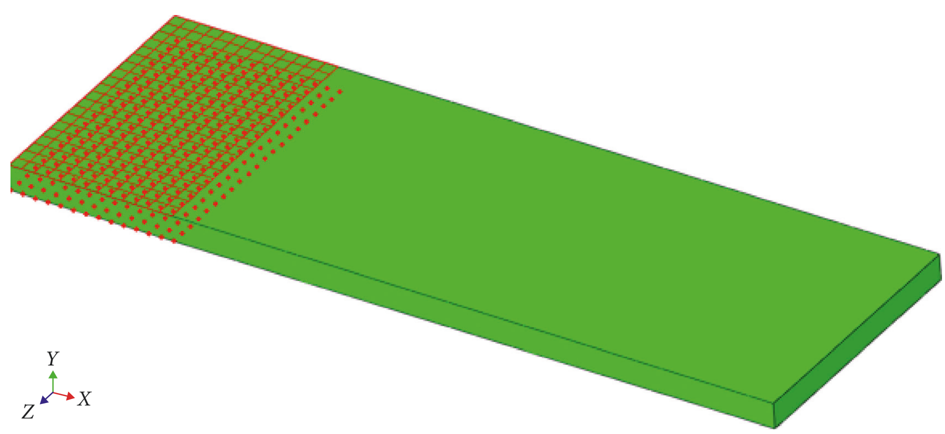

Figure 2: Electric load application to the electrode tape, which takes into account the circularity of the electrocontact surfacing.

Finite element modulation of the electrocontact surfacing by tape was performed for the following initial parameters:

(i) Diameter of the roller electrode: 100 mm

(ii) Tape width: 3.2 mm

(iii) Tape thickness: 0.5 mm

(iv) Force on the roller electrode: 2 kN

(v) Surfacing current: 6 kA

Material and mechanical properties of the tape are given in Tables 1–4.

4. Results

As an example, Figures 3–5 show the temperature field of the electrode steel tape in the time interval of the surfacing current impulse: the rotation speed of the part $V_{\text{part}} = 0.4\,\text{sec}^{-1}$ and the speed of rotation of the roller electrode $V_{\text{r}} = 0.203\,\text{sec}^{-1}$. According to the obtained data, the electrode material heating is initiated in the area of its contact with the surface of the part. At the same area of the tape, in the thermodeformation hearth, there are the maximum temperatures during the whole heating period. Such a nonuniform distribution of the space-time temperature field over the electrode material thickness indicates the melting of the tape in the contact zone with the surface of the part. The main part of the electrode material in the thermal deformation source in the tough-plastic state is caused by heating up to 911–1010°C. Comparatively low values of temperature indices in the contact zone of the electromagnetic tape with the roller electrode are caused by the intensive removal of heat from it, which is released in the electrode tape material during the electrocontact surfacing. Thus, there is no sticking of the electrode metal with the roller electrode.

Comparison of the modeling results of spatiotemporal heat fields for different durations of electric current impulse

Table 1: The chemical composition of the material of the electrode tape.

C (%)	Si (%)	Mn (%)	Ni (%)	S (%)	P (%)	Cr (%)	Cu (%)	As (%)
0.05–0.12	<0.03	0.25–0.5	<0.3	<0.04	<0.035	<0.1	<0.3	<0.08

Table 2: Mechanical properties of the electrode tape at $T = 20°C$

Tensile strength (MPa)	Yield strength (MPa)	Relative extension (%)	Degree of use of plasticity stock (%)	Brinell hardness $\cdot 10^{-1}$ (MPa)
290	175	35	60	179

Table 3: Physical properties of the electrode tape depending on the heating temperature.

T (°C)	$E{\cdot}10^5$ (MPa)	$\alpha{\cdot}10^6$ (1/deg)	λ (W/(m·deg))	ρ (kg/m^3)	C (J/(kg·deg))	$R{\cdot}10^9$ (Ohm·m)	G (Ohm^{-1})	ν
1	2	3	4	5	6	7	8	9
100	2.08	12.5	60	7846	482	178	3984	0.265185
200	2.03	13.4	56	7814	498	252	3115	0.271666
300	1.97	14	51	7781	514	341	2451	0.278148
400	1.89	14.5	47	7745	533	448	1957	0.284629
500	1.77	14.9	41	7708	555	575	1590	0.291111
600	1.63	15.1	37	7668	584	725	1318	0.297592
700	1.4	15.3	34	7628	626	898	1085	0.304074
800	1.2	14.7	30	7598	695	1073	899	0.310555
900	1.0	12.7	27	7602	703	1124	865	0.317037

Table 4: Yield strength σ_T depending on plastic deformation δ and heating temperature T.

σ_T (MPa)	δ (mm)	T (°C)
175,0	0.0	20
818,8	0.5	20
936,25	1.0	20
49,24	0.0	500
163,76	0.5	500
187,25	1.0	500
28,44	0.0	600
94.57	0.5	600
108.14	1.0	600
17.88	0.0	700
59.45	0.5	700
67.98	1.0	700
11.96	0.0	800
39.77	0.5	800
45.47	1.0	800
8.39	0.0	900
27.89	0.5	900
31.89	1.0	900
6.11	0.0	1000
20.31	0.5	1000
23.22	1.0	1000
4.58	0.0	1100
15.24	0.5	1100
17.43	1.0	1100
3.53	0.0	1200
11.73	0.5	1200
13.41	1.0	1200
2.77	0.0	1300

behavior (Figures 4 and 5) testifies to the leveling of the temperature gradient in the thermal deformation hearth both along the length and width of the tape with increasing current impulse running time.

With a duration of the electric current impulse, $t_{imp} = 0.04$ sec, a local temperature increase is observed in the thermodeformation hearth with a preferential displacement of the thermal spot into the alloying zone of the tape with the surface of the part (Figure 4). The maximum of temperature indices with a value of 1200°C in the zone of contact of the tape with the surface of the product ensure the alloying in this area with a cast zone formation, which contributes to the creation of a coating with the necessary strength of adhesion to the base metal.

In the zone of contact with the roller electrode, the thermal spot is characterized by lower temperatures, which is explained by the significant heat removal into the copper water-cooled roller electrode. In all the considered cases, heating of the surfacing zone is accompanied by the insignificant heat removal in adjacent to the thermal deformation hearth areas of the electrode material. The increase in the duration of the current impulse during the electrocontact surfacing, with the other constant process parameters (current strength and stress at the roller electrode) according to the obtained results (Figure 5), provides heating over the whole thickness of the tape in the thermal deformation zone to the temperature $T = 1200°C$. This with a further increase in the time of the current impulse can lead to burn through or splash of the molten electrode material, adversely affecting the quality of the deposited layer and restoring the whole product.

In order to study the effect of the electric current impulse duration on the change in the picture of the stress-strain state of the electrode tape in the thermal deformation zone, a modeling of the process at $K_v = 1.015$ and $K_v = 1.0$ was carried out. Figures 6–11 show the results of the finite element modulation of the stress-strain state of the tape in the thermal deformation center, depending on the duration of

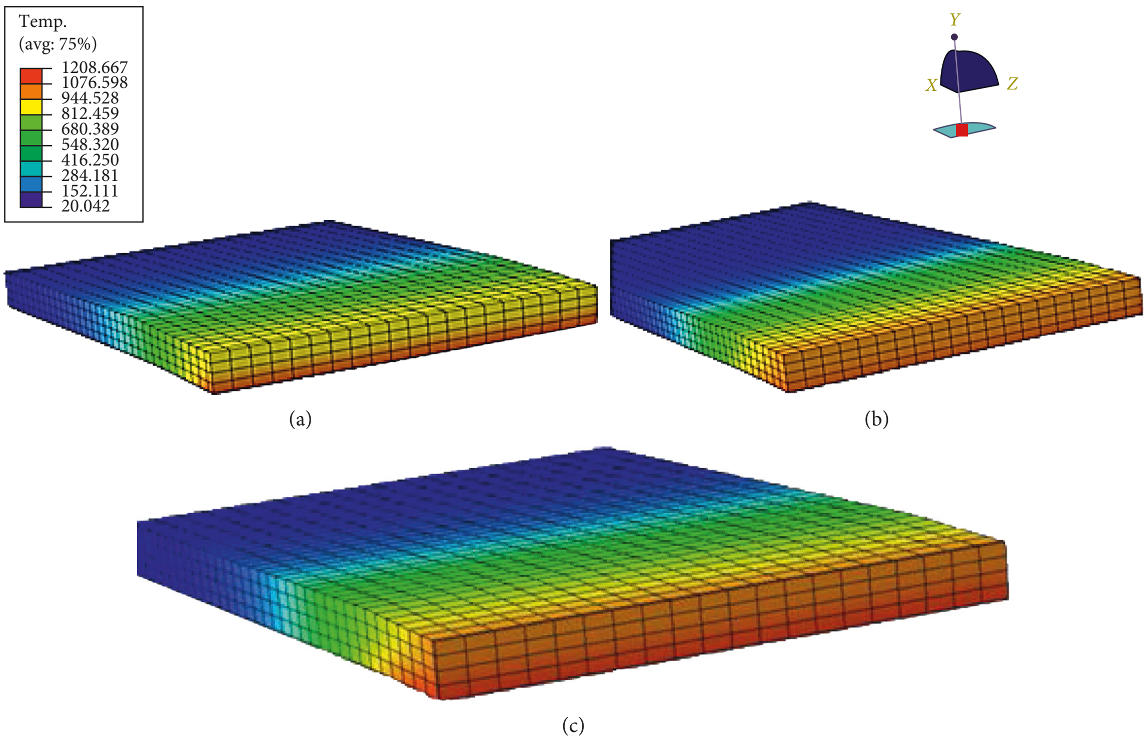

FIGURE 3: Distribution of temperature fields in the process of electrocontact surfacing during an electric current impulse $t_{imp} = 0.04$ sec: in 0.02 sec of the current pulse behavior (a); in 0.03 sec of the current pulse behavior (b); at the exit from the thermal deformation hearth (c).

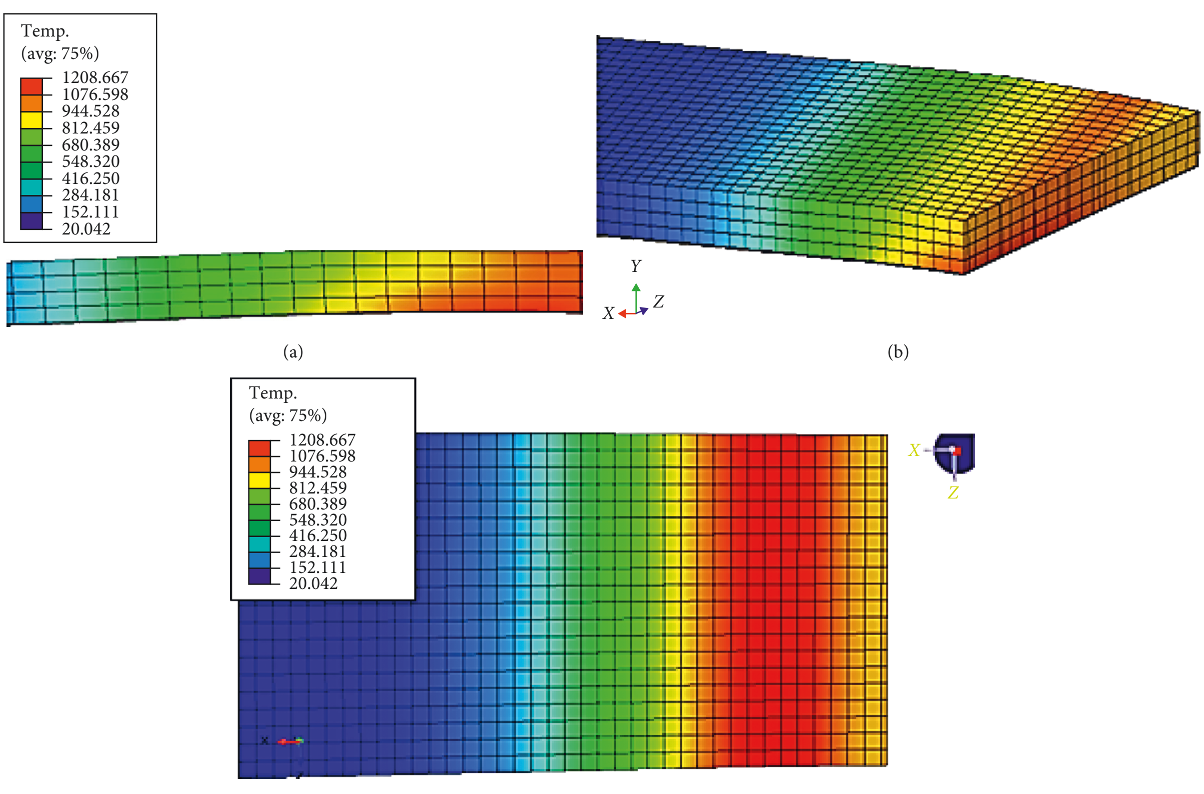

FIGURE 4: The general form of the temperature field of a steel strip in a thermal deformation hearth (a, b) and the distribution of thermal fields in the zone of the tape contact with the surface of the component (c) in the process of electrocontact surfacing at the outlet from the thermal deformation hearth $t_{imp} = 0.04$ sec.

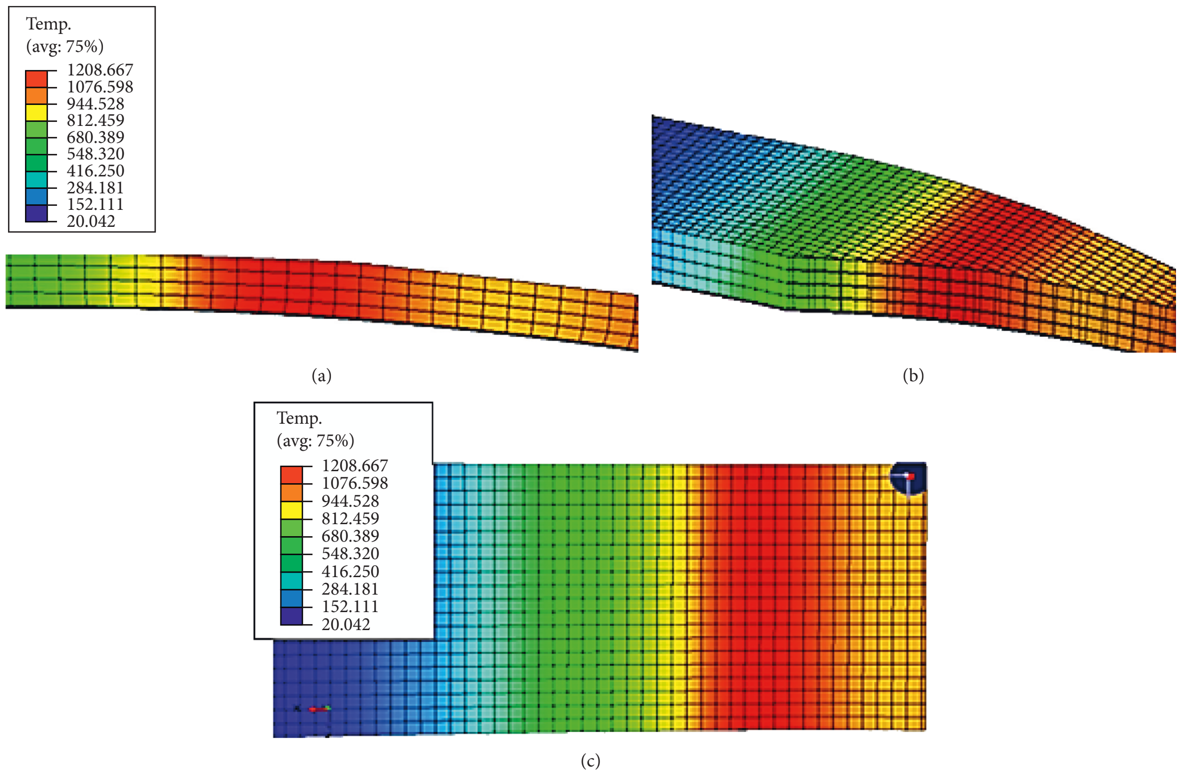

Figure 5: General view of the temperature field of a steel tape in the thermal deformation hearth (a, b) and the distribution of thermal fields in the zone of tape contact with the surface of the part (c) in the electrocontact surfacing at $t_{imp} = 0.05$ sec.

the surfacing current impulse in the electrocontact surfacing: the rotation speed of the part $V_{part} = 0.4\ sec^{-1}$, the rotation speed of the roller-electrode $V_r = 0.39\ sec^{-1}$, and the kinematic asymmetry coefficient $K_v = 1.015$.

According to the obtained data (Figures 6–8), the maximum equivalent stresses during the whole time of the current impulse occur in the thermal deformation hearth in the zone of contact of the electrode tape with the surface of the part. This is agreed with the calculated data of the developed finite difference mathematical model [20] and normal contact stresses. The increase in the time of the surfacing current impulse helps to reduce the value of the equivalent stresses. Thus, at the time of the current impulse, $t_{imp} = 0.03$ sec, the maximum value of the equivalent stresses is 115 MPa. And, this value is observed over the whole thickness of the electrode tape in the thermal deformation hearth (Figure 6). With an increase in the time of the current impulse to 0.04 sec, the maximum values of equivalent stresses decrease to 110 MPa and move mainly to the contact zone of the electrode tape with the surface of the part (Figure 7). This is caused by the process of electrode strip metal relaxation, which is in a tough-plastic state. With an increase in the time of the electric current impulse, the overall heating temperature of the metal increases over the thickness of the electric tape, which reduces the value of the equivalent stresses.

High values of equivalent stresses up to 110 MPa in the alloyage zone, which has the highest temperature in the thermal deformation zone (about 1200°C), are caused by the frictional forces. They are caused by the kinematic asymmetry of the electrocontact surfacing process.

Further increase in the duration of the current impulse to 0.05 sec results in a shift of the maximum values of the equivalent deformation to the side of the contact zone of the tape with the roller electrode and to a general decrease in their value (Figure 8).

Thus, a further increase in the overall heating temperature of the electrode material, which with the duration of the electric current impulse $t_{imp} = 0.05$ sec will be 1200°C along the whole thickness of the electrode strip (Figure 5), will lead to a decrease in the value of the equivalent stresses in the fusion zone, even with a kinematic asymmetry of the electrocontact surfacing process due to the expansion of the heating region and increase in the residence time of the thermodeformation focus in the heated state. This is due to the fact that design of the roller electrode of the contact machine for electrocontact surfacing provides the cooling of the roller electrode. This avoids welding the tape to the surface of the roller electrode. An increase in the duration of the current pulse leads to an increase in the temperature of the tape in the surfacing zone as a whole. However, in the zone of contact of the tape with the roller electrode, it is forcibly cooled, and in the zone of contact with the surface of the part, its temperature rises significantly. This helps to increase the equivalent stresses in the zone of contact of the tape with the roller electrode.

At the same time, equivalent stresses in the contact zone of the tape with the surface of the part will be 60–70 MPa,

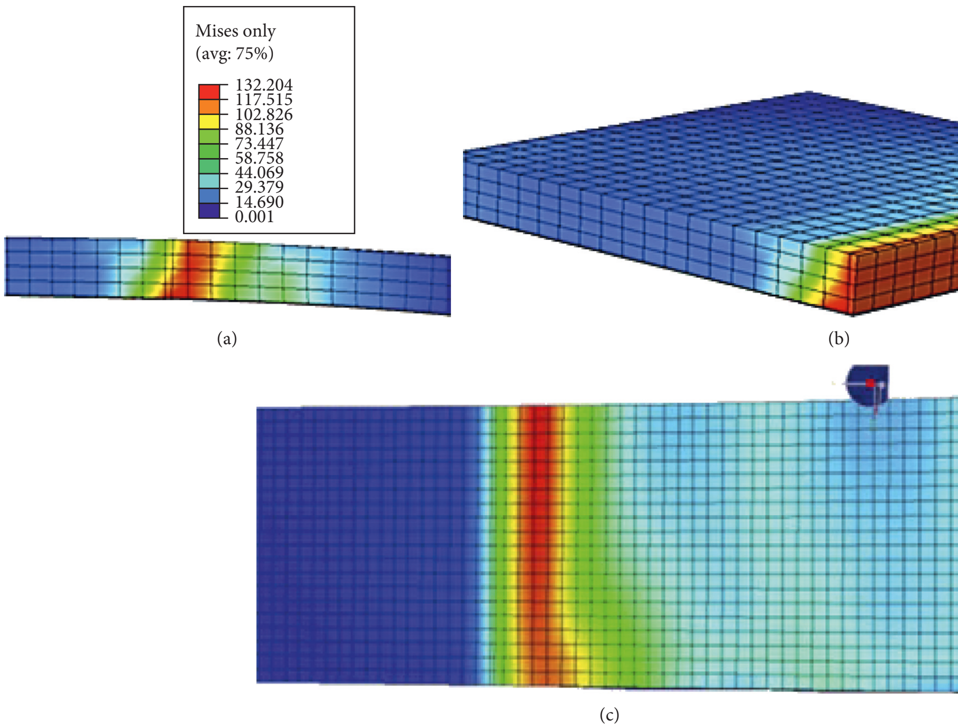

Figure 6: The distribution of equivalent stresses in the thermodeformation hearth (a, b) and in the contact zone of the tape with the surface of the part (c) during the electrocontact surfacing of the steel tape at $K_v = 1.015$ and the duration of the current impulse $t_{imp} = 0.03$ sec.

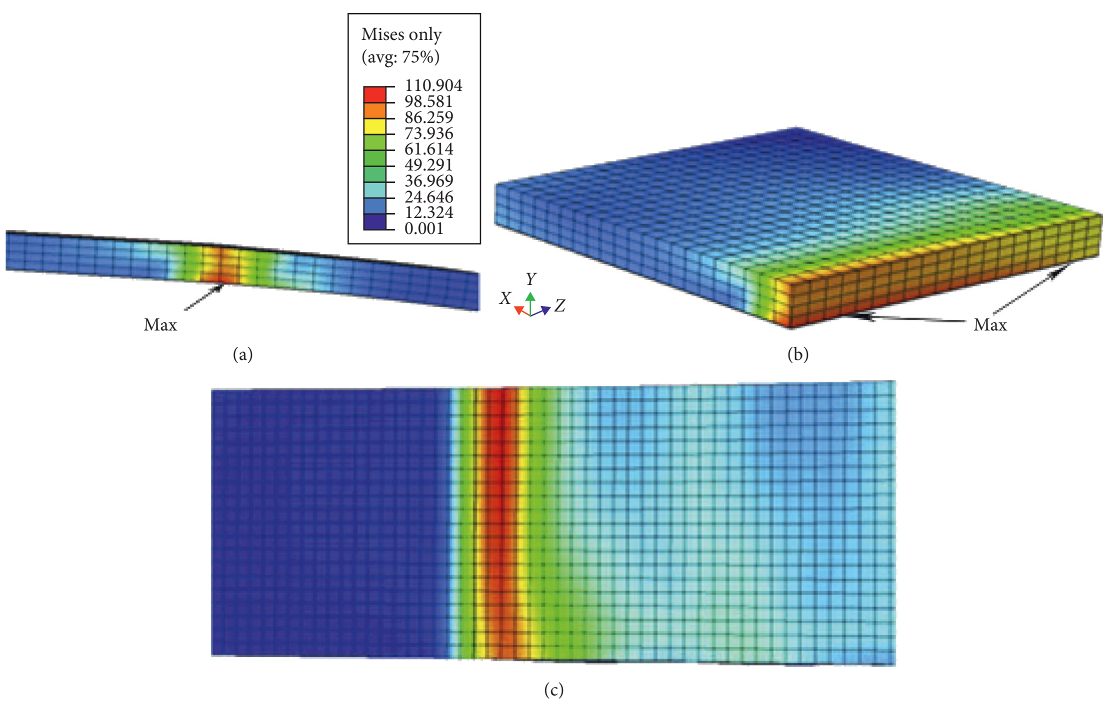

Figure 7: The distribution of equivalent stresses in the thermodeformation hearth (a, b) and in the zone of contact of the tape with the surface of the part (c) in the case of electrocontact surfacing with steel tape at $K_v = 1.015$ and the duration of the current pulse $t_{imp} = 0.04$ sec.

and in the contact zone with the roller electrode, it will be 100–110 MPa, which is related to the less plastic state of the tape in the area of its contact with the roller electrode due to the removal from its surface a certain amount of heat.

According to the results of the presented finite element modulation (Figures 9–11), in the contact zone of the electrode tape with the roller electrode surface, the deformation processes practically do not occur which is caused

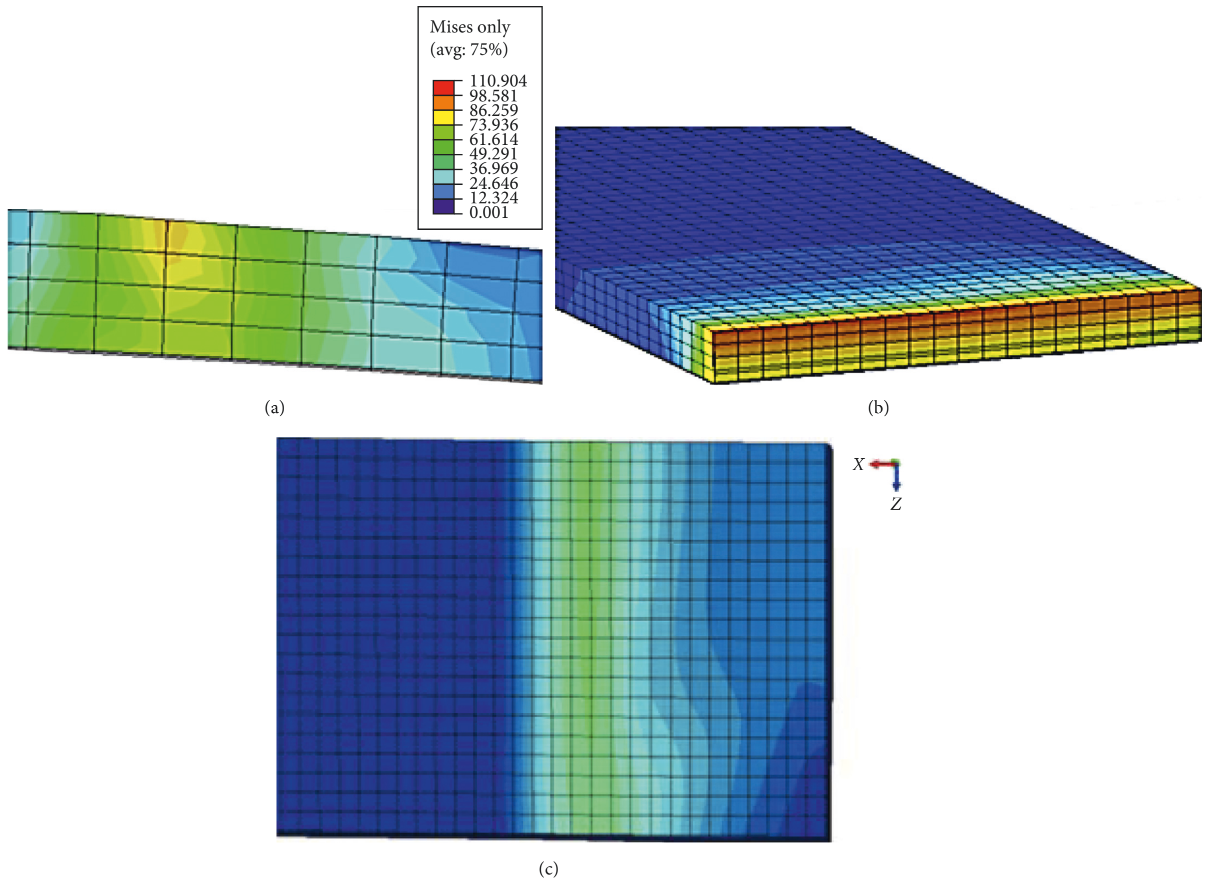

Figure 8: The distribution of equivalent stresses in the thermodeformation hearth (a, b) and in the zone of contact of the tape with the surface of the part (c) in the case of electrocontact surfacing with steel tape at $K_v = 1.015$ and the duration of the current pulse $t_{imp} = 0.05$ sec.

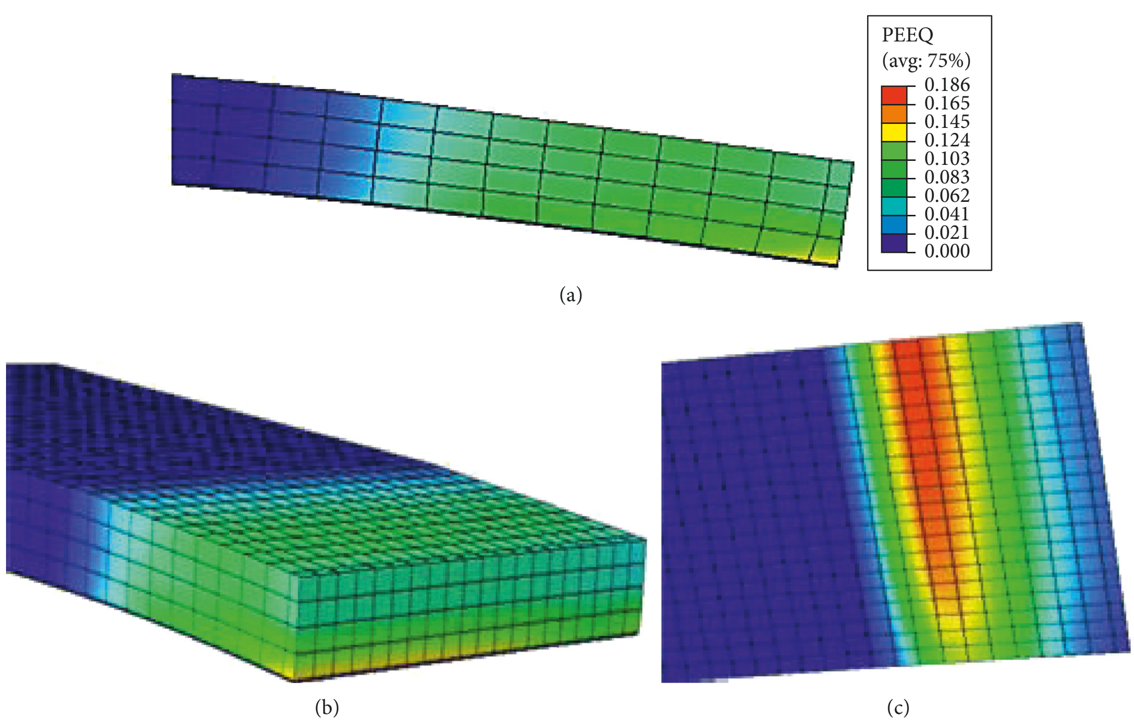

Figure 9: The distribution of equivalent deformations in the thermodeformation hearth (a, b) and in the zone of contact of the tape with the surface of the part (c) with the electrocontact surfacing of the steel tape at $K_v = 1.015$ and the duration of the current impulse $t_{imp} = 0.03$ sec.

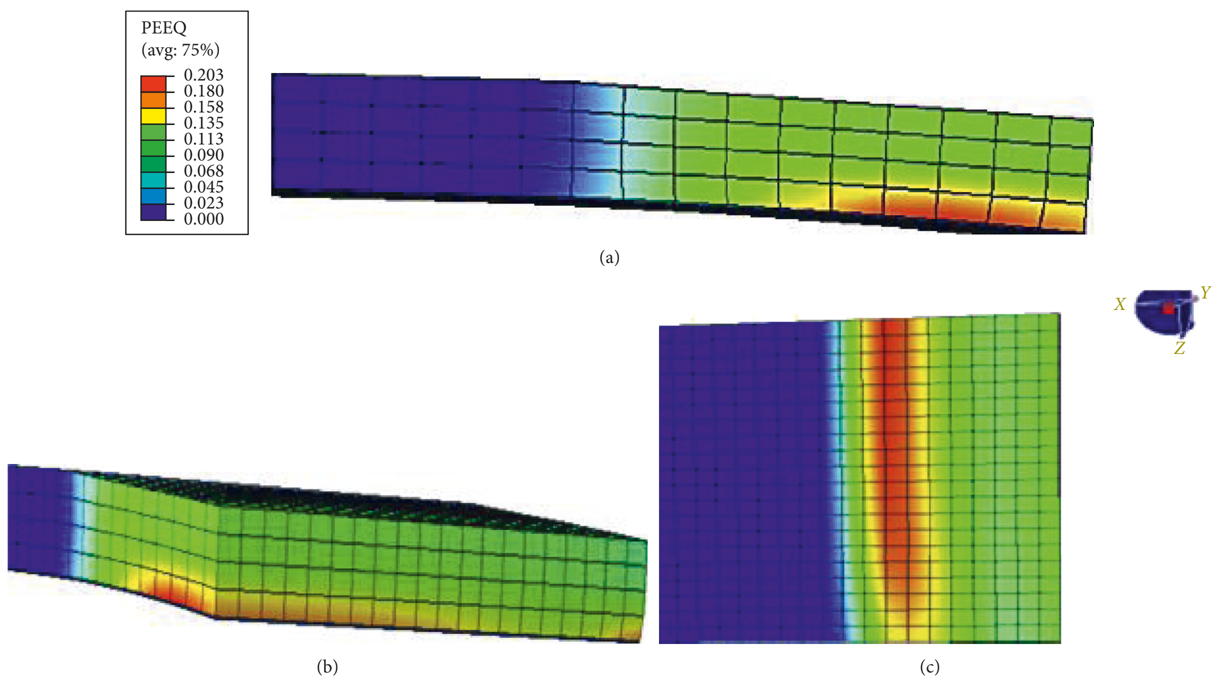

FIGURE 10: The distribution of equivalent deformations in the thermal deformation hearth (a, b) and in the zone of tape contact with the surface of the part (c) in the case of electrocontact surfacing with a steel tape at $K_v = 1.015$ and the duration of the current impulse $t_{imp} = 0.04$ sec.

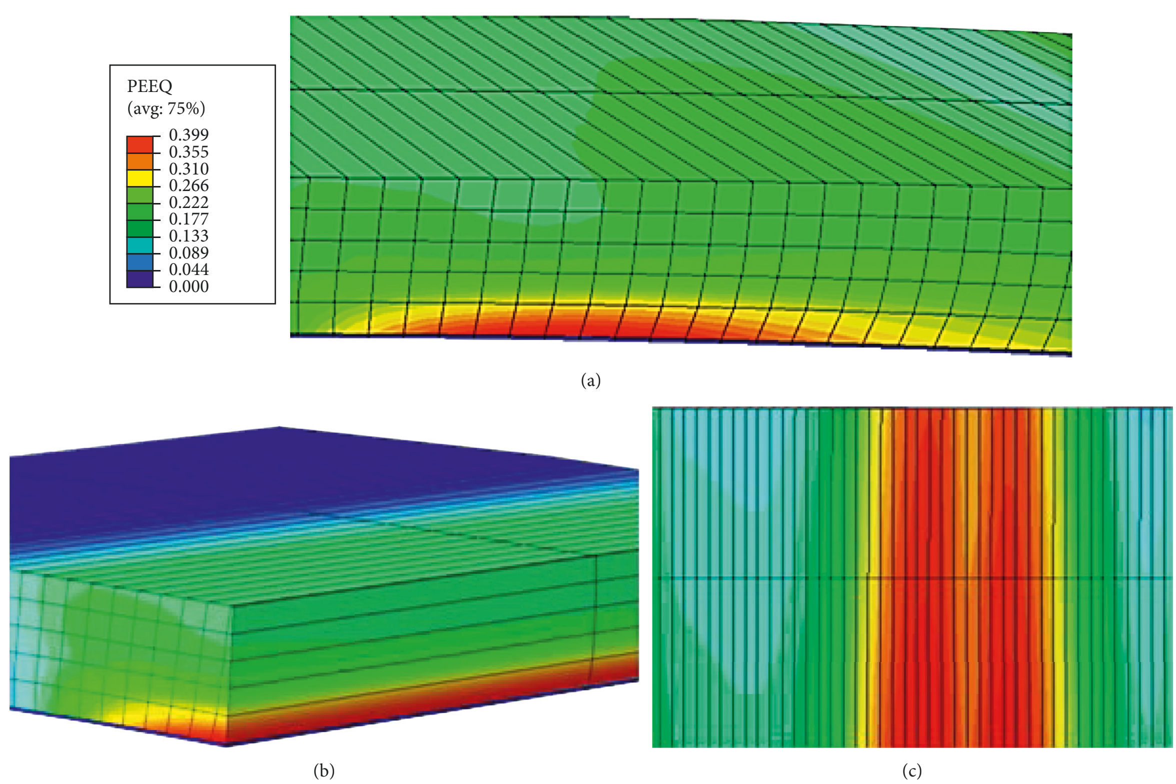

FIGURE 11: The distribution of equivalent deformations in the thermodeformation hearth (a, b) and in the zone of contact of the tape with the surface of the part (c) with the electrocontact surfacing of the steel tape at $K_v = 1.015$ and the pulse duration $t_{imp} = 0.05$ sec.

by the low values of tangential contact stresses typical for this section of the tape thickness at $K_v = 1.015$ and also with a comparatively low temperature of the material in this zone. On the other hand, equivalent deformations are characterized by maximum values in the zone of contact of the steel tape with the surface of the part. This pattern is observed when the impulse width of the surfacing current is increased and correlated very accurately with the data of the developed mathematic finite difference model of the electrocontact surfacing on the tape.

Besides, higher values of equivalent deformations in the contact zone of the electrode tape with the surface of the part are explained by an increase in the temperature in the thermal deformation zone, which contributes to the intensification of deformation processes and to the qualitative formation of the coating. The contact zone of the electrode tape with the roller electrode is characterized by lower temperatures ($T = 911^{\circ}$C) than the contact zone of the tape with the surface of the part ($T = 1200^{\circ}$C) (Figure 3(b)), which causes a decrease in the value of the equivalent deformation up to 0.093, as compared with 0.186 in the fusion zone (Figure 9). With the duration of the current impulse $t_{imp} = 0.03$ sec, equivalent stresses are 115 MPa and are distributed over the whole thickness of the tape in the thermal deformation zone (Figure 6). In the fusion zone, the area of equivalent stresses increases, according to the results of finite element analysis (Figure 6), which together with the influence of temperature contributes to double the equivalent deformations in this area (Figure 9).

The increase in the time for the surfacing current impulse up to 0.04 sec causes an increase in the maximum value of the equivalent deformations in the thermodeformation hearth to 0.203 (Figure 10). According to the initial conditions for the development of a finite element model of the electrocontact surfacing, the heat removal from the surface of the electrode tape to the water-cooled roller electrode in the contact zone was taken into account. This affected the simulation results in the calculation of equivalent deformations: in the contact zone with a roller electrode with an increase in the duration of the electric current to 0.04 sec, they practically do not change and amount to 0.101 (Figure 10). Moreover, the decrease in the value of the equivalent stresses at $t_{imp} = 0.04$ sec to 110 MPa in the fusion zone (Figure 7) does not affect the level of equivalent deformations in this section. This is caused by the predominant effect on the deformation processes of the expansion of the metal heating zone of the electrode strip to 1200°C in the thermodeformation hearth (Figure 4), that is, with the increase in the amount of material in the plastic state. This also allows expanding the area of the deformable metal in the zone of the tape contact with the surface of the part, which increases the adhesion strength of the coating to the surface of the part (Figure 10) and correlated with data [24–26].

With an increase in the time of the surfacing current impulse to 0.05 sec, the value of equivalent deformations is doubled (Figure 11). Moreover, such an increase is observed both in the zone of contact with the surface of the electrode tape products (equivalent strain is 0.399) and the tape contact zone of the roller electrode (equivalent strain is 0.190). This is due to the overall increase in temperature over the thickness of the electrode strip. Thus, the temperature in the zone of contact with the roller electrode will be 1100°C and the contact with the component surface area will be 1200°C (Figure 5). Moreover, in the contact area of the tape and parts' surface, equivalent strains increase due to the high temperatures, and in the zone of contact with the roller electrode, they have maximum values (110 MPa) due to combined influence of heating and equivalent stresses at $t_{imp} = 0.05$ sec (Figure 8). Such an increase in the equivalent deformations along the cross section of the electrode strip in the thermal deformation zone indicates that further increase in the duration of the surfacing current impulse at $K_v = 1.015$ can lead to considerable deformations of the electrode strip and it is unreasonable.

The results of the finite element analysis at $K_v = 1.0$ indicate a decrease in the value of equivalent stresses along the cross section of the electrode tape in the thermal deformation zone from 100 MPa at $t_{imp} = 0.03$ sec (Figure 12) to 90 MPa at $t_{imp} = 0.04$ sec (Figure 13). In the first case, the maximum values of equivalent stresses are observed over the whole thickness of the electrode tape, and in the second case, the largest equivalent stresses are concentrated mainly in the zone of contact of the tape with the roller electrode and in the fusion zone. This type of distribution is caused by the heating time of the electrode material, as in the cases with $K_v = 1.015$ (Figures 6–8) and is explained by the fact that, in some areas, the material becomes more plastic, and in some cases, it remains elastic due to the maldistribution of temperature fields.

The increase in the duration of the current impulse to $t_{imp} = 0.05$ sec, as in the case with $K_v = 1.015$ (Figure 8), helps to reduce the equivalent stresses in the zone of contact of the tape with the surface of the part due to the increase in the area of the material with a temperature of 1200°C (Figure 14). The value of equivalent stresses is reduced to 60–75 MPa. In all three cases, regardless the duration of the surfacing current impulse, the area of equivalent stresses activity in the zone of contact of the tape with the roller electrode is equal to the area of their activity in the zone of contact of the tape with the surface of the part (Figures 12–14). However, at $K_v = 1.015$, there is the increase in the area of equivalent stresses activity from the contact zone with the roller electrode toward the fusion zone, which is most noticeable with a moderate heating of the electrode material $t_{imp} = 0.03$ sec (Figure 6).

When studying the effect of the current impulse duration on the variation of equivalent deformations, the same pattern is observed, as in the case of electrocontact surfacing with $K_v = 1.015$. The difference is in decreasing the value of the equivalent strains at $K_v = 1.0$, in comparison with $K_v = 1.015$ for the same values of the surfacing current pulse duration (Figure 15). The general regularity of the increase in equivalent deformations is the same in both symmetrical and asymmetrical processes, with an increase in temperature, that is, with an increase in the amount of material heating to 1200°C. At $K_v = 1.0$ and $t_{imp} = 0.05$ sec, the maximum value of the equivalent strain is 0.280 (Figure 15), while at $K_v = 1.015$ and $t_{imp} = 0.05$ sec, it reaches 0.380 (Figure 11). In the contact zone of the electrode tape with the roller electrode at $K_v = 1.0$ and $t_{imp} = 0.05$ sec, the equivalent deformations do not exceed 0.187 (at $K_v = 1.015$ and $t_{imp} = 0.05$ sec, the equivalent deformations in this area are 0.190). This confirms the hypothesis about the effect of the

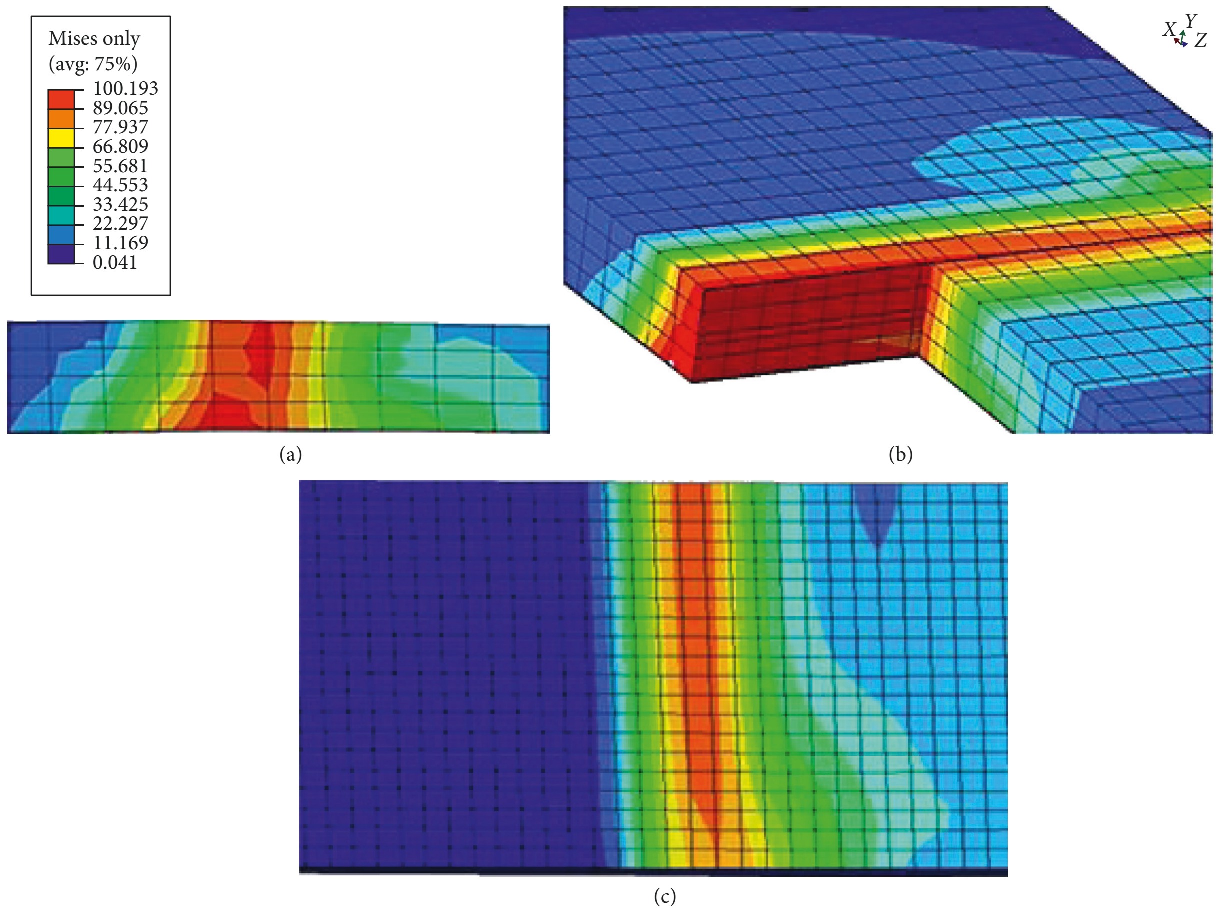

Figure 12: The distribution of equivalent stresses in the thermal deformation hearth (a, b) and in the zone of contact of the tape with the surface of the part (c) in the case of electrocontact surfacing with a steel tape at $K_v = 1.0$ and the pulse duration of the current $t_{imp} = 0.03$ sec.

electrocontact surfacing kinematic asymmetry coefficient on the deformation processes during the coating by the electrochemical method, and, consequently, on the formation of the interconnection as a whole and its bonding strength.

Thus, one of the methods of increasing the adhesion strength due to the intensification of deformation processes in the fusion zone is the increase in the time of the electric current impulse. But both with the kinematic asymmetry of the electrocontact surfacing process and without it, this method causes a rapid change in the stress-strain state, which is difficult to control under the transient nature of the coating process. Therefore, it is advisable to control the process of electrocontact surfacing by using tapes by the construction of the kinematic asymmetry of the process.

The kinematic asymmetry coefficient K_v effect on the change in tangential contact stresses in the contact area of the electrode material with the surface of the roller electrode and the part to be reconstructed was analyzed (Figures 16–19). According to the calculated data, the minimum values of tangential contact stresses are observed at the value of the kinematic asymmetry coefficient $K_v = 1.0$, that is, without the asymmetry of electrocontact surfacing by using tapes. Their value under such conditions of the electrocontact surfacing process is 25 MPa. Moreover, the spread areas in the contact zone of the electrode tape with the roller electrode and in the contact zone with the part's surface are equivalent (Figure 16).

It is established that an increase in K_v to 1.015 leads to an increase in the tangential contact stresses in the contact area of the electrode material with the surface of the remanufactured part ($\tau_{xi1} = 38$ MPa), while in the contact zone with the roller electrode, these stresses practically do not change ($\tau_{xi2} = 26$ MPa), which is consistent with the calculated data of the developed mathematical model [22]. The area of distribution of tangential contact stresses also changes: in the zone of contact of the electrode tape with the surface of the part, they occupy a much larger area than in the contact zone of the tape with the roller electrode (Figure 17).

With an increase in K_v to 1.025, τ_{xi1} increases to 45 MPa in the contact area of the electrode tape with the surface of the part. In the contact zone of the tape with the roller electrode, there is also an increase in tangential contact stresses: τ_{xi2} is 35 MPa (Figure 18). However, there is also an increase in the area of distribution of τ_{xi2} in the contact zone of the electrode material with the roller electrode.

Further increase in the kinematic asymmetry coefficient is unreasonable since even at $K_v = 1.075$, the tangential contact stresses in the contact zone of the electrode material with the roller electrode occupy a considerable area, which can hinder the qualitative formation of the deposited layer

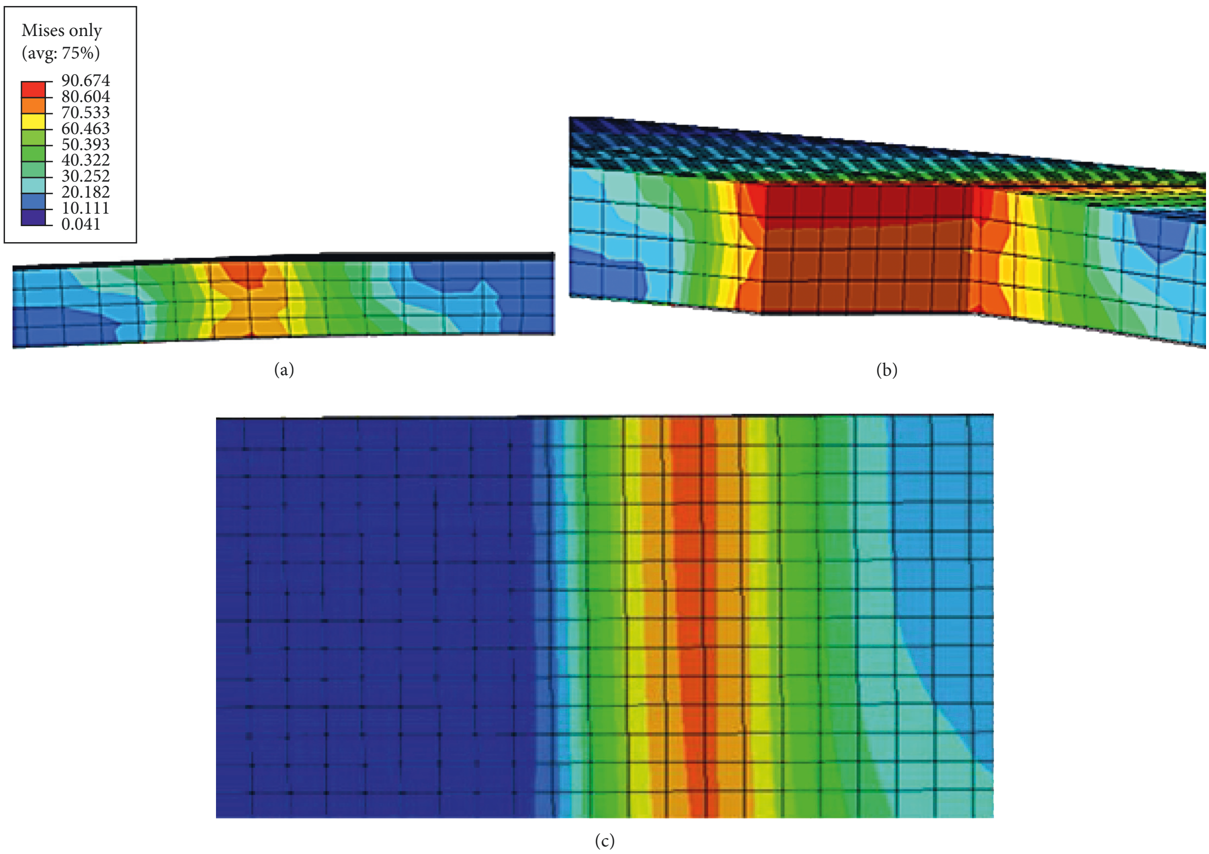

Figure 13: The distribution of equivalent stresses in the thermal deformation hearth (a, b) and in the zone of tape contact with the surface of the part (c) in the electrocontact surfacing of the steel strip at $K_v = 1.0$ and the impulse width of the current $t_{imp} = 0.04$ sec.

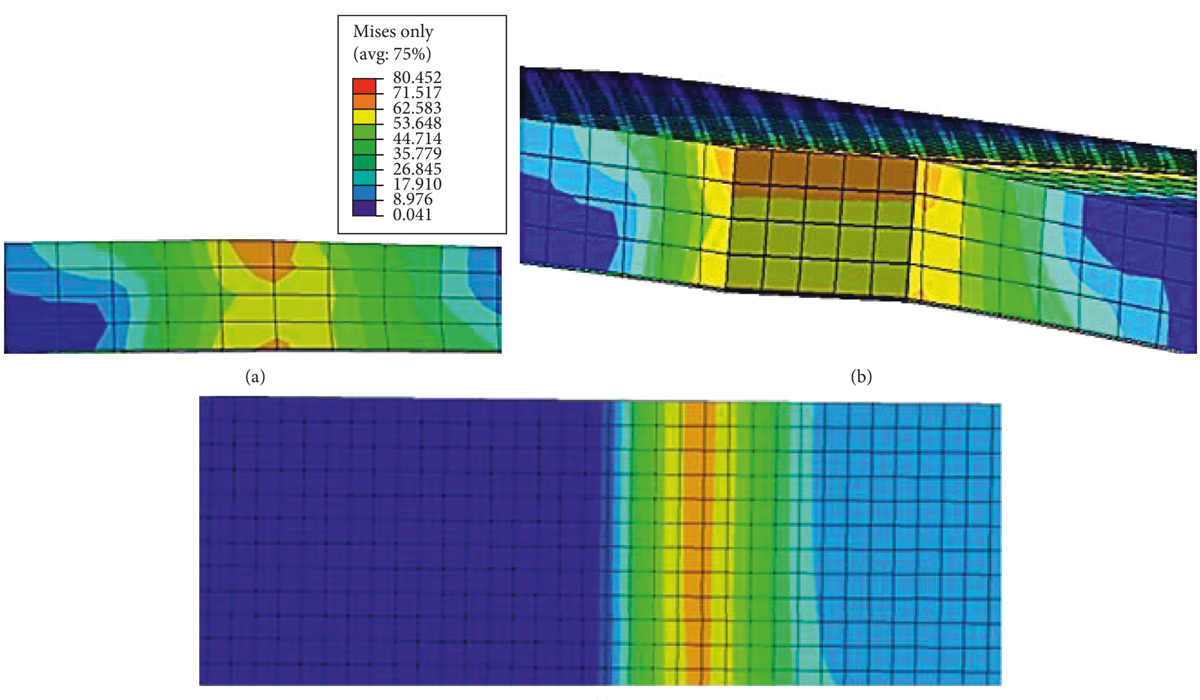

Figure 14: The distribution of equivalent stresses in the thermal deformation hearth (a, b) and in the contact zone of the tapes with the surface of the part (c) in the case of electrocontact surfacing of the steel tape at $K_v = 1.0$ and the impulse width of the current $t_{imp} = 0.05$ sec.

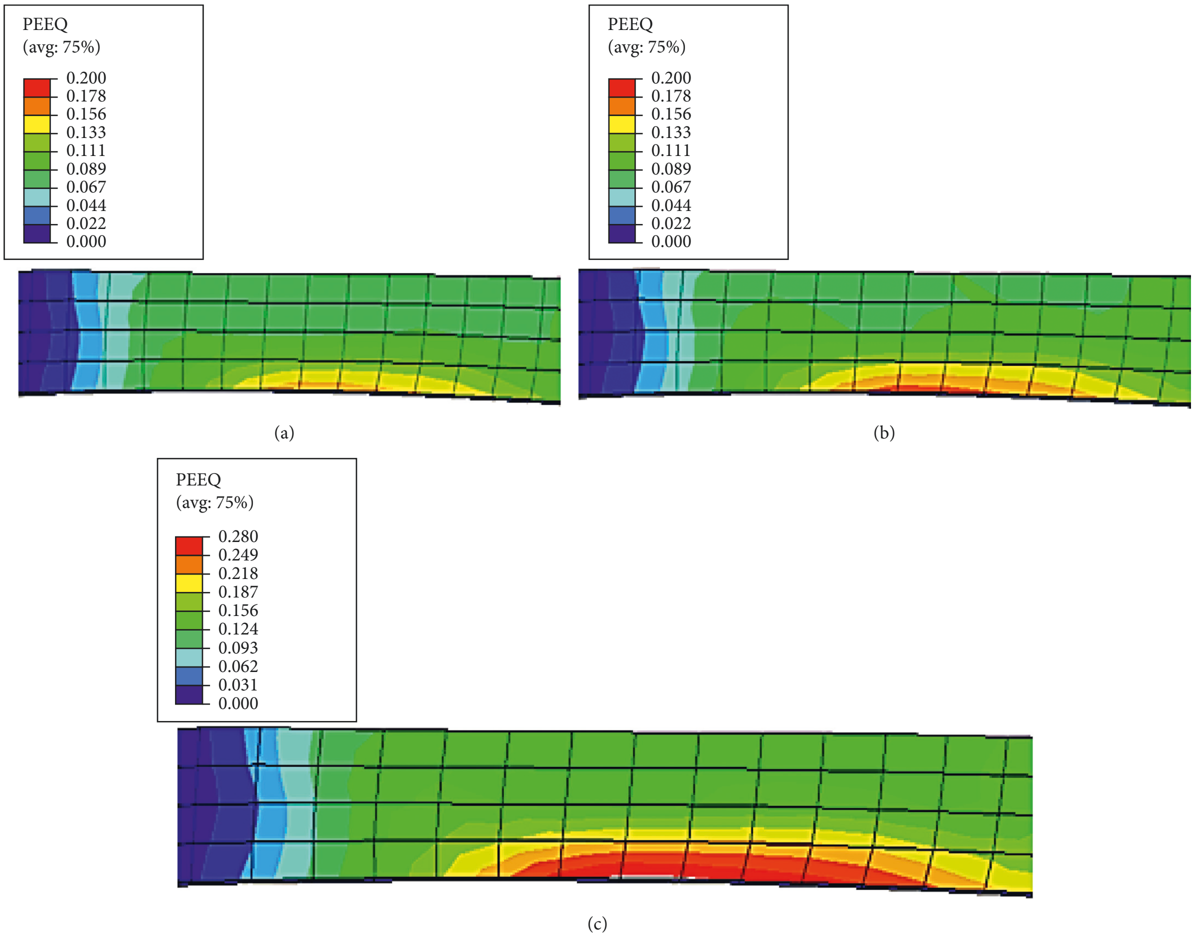

FIGURE 15: The distribution of equivalent deformations in the thermal deformation hearth in electrocontact surfacing of a steel tape at $K_v = 1.015$ and the duration of a current impulse: $t_{imp} = 0.03$ sec (a), $t_{imp} = 0.04$ sec (b), and $t_{imp} = 0.05$ sec (c).

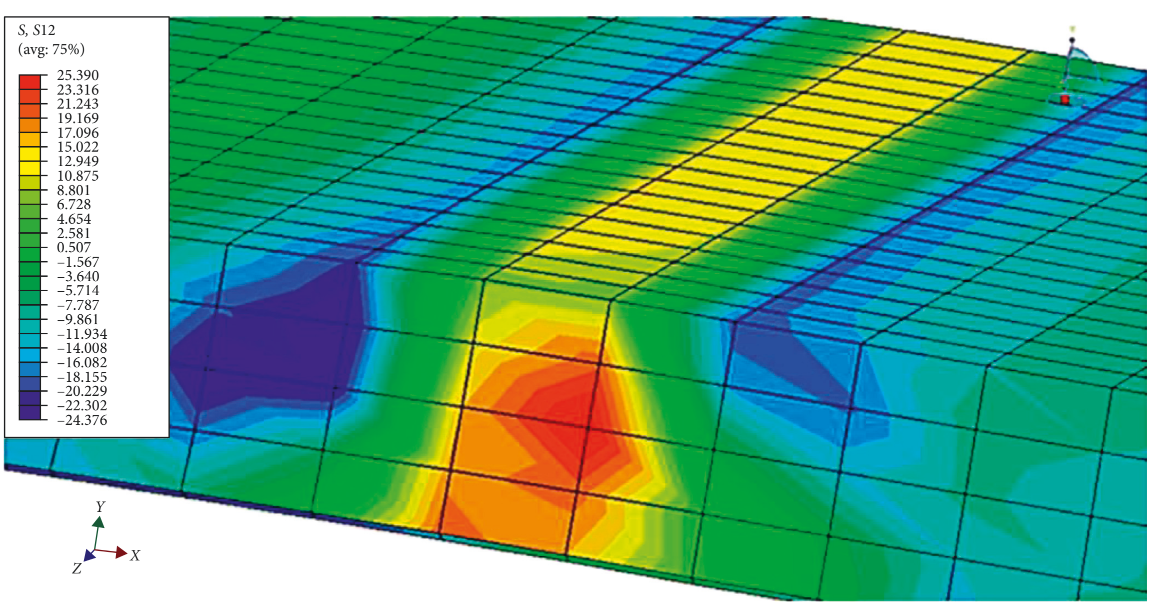

FIGURE 16: Distribution of tangential contact stresses in a thermal deformation hearth at $K_v = 1.0$.

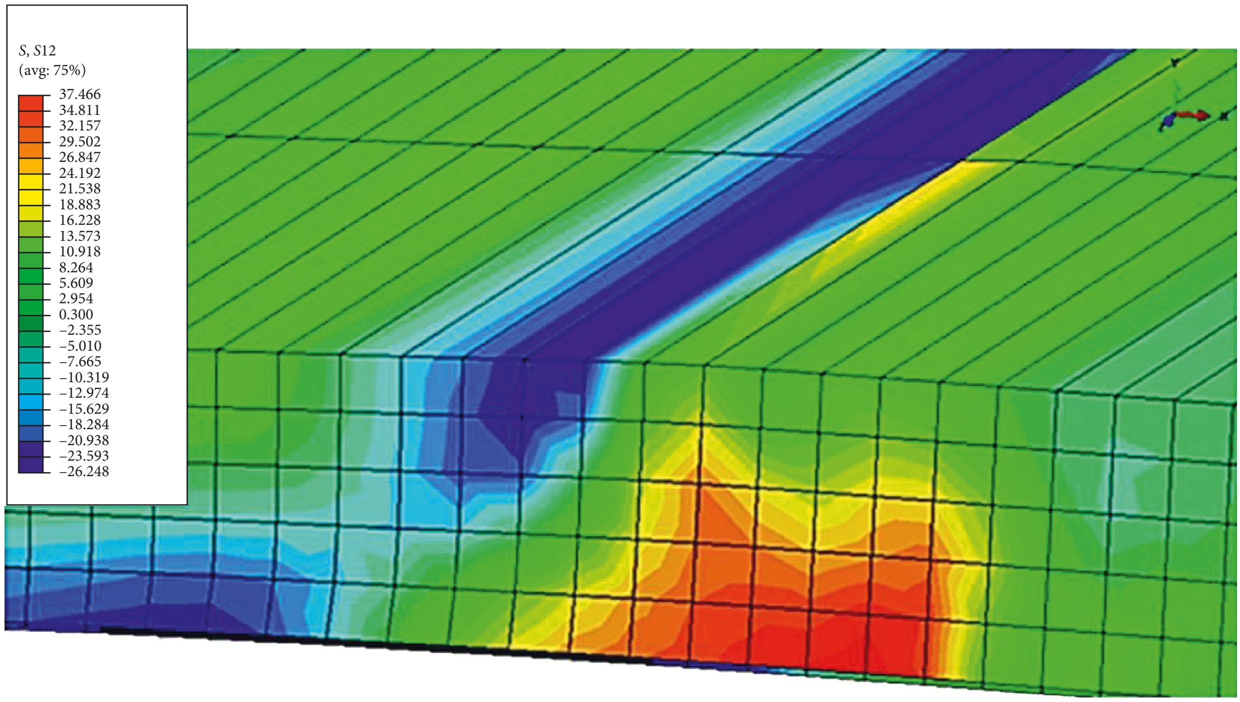

Figure 17: The distribution of the tangential contact stresses in the thermal deformation hearth at $K_v = 1.015$.

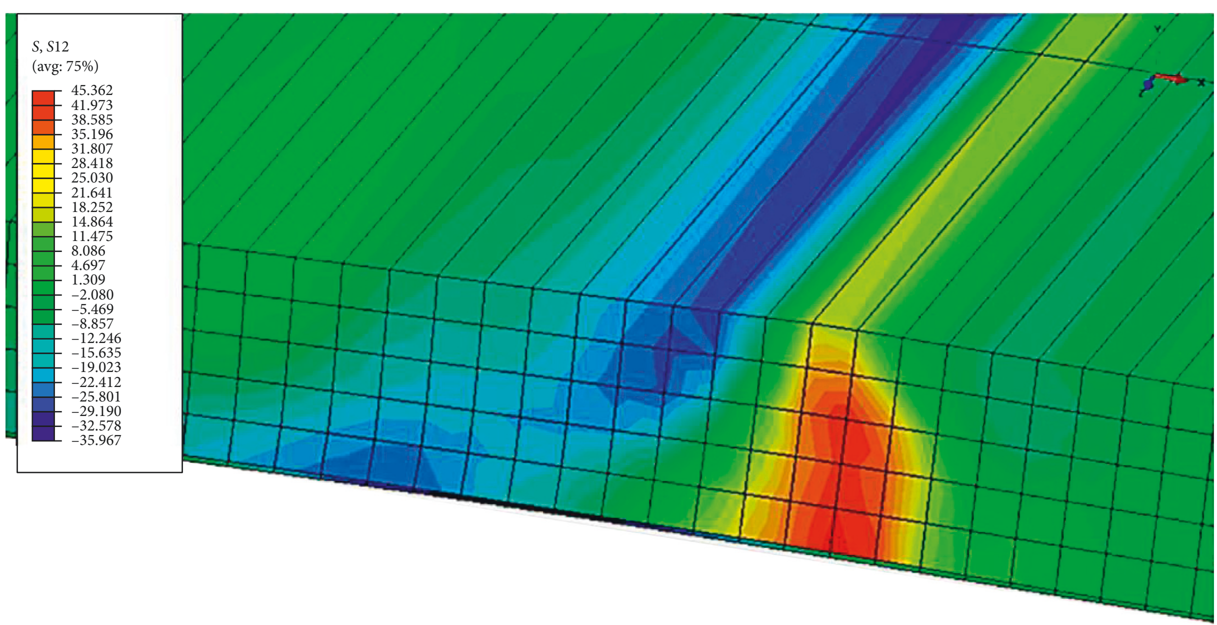

Figure 18: The distribution of tangential contact stresses in a thermal deformation hearth at $K_v = 1.025$.

due to adherence of the electrode material to the surface of the roller electrode and contribute to the tool wear.

5. Comparison

According to the obtained data (Figure 20), the error in calculating the finite difference model when compared with the results of the finite element model does not exceed 10.2%, which indicates the adequacy of the proposed models.

The adhesion strength of the deposited layer was determined by breaking off the pin by a normally applied force on Staffens samples with the length of 20 mm and diameter of 4 mm on a tensile-testing machine R-20 GOST 7855-74.

The results of the experiment (Figure 21), carried out on the welded samples at $R_z = 50$ mm, $I = 6.5$ kA, and $P = 1.5$ kN, showed that, at $K_v = 1.015$, the adhesion strength of the welded layer to the base metal is maximal.

A further increase in the kinematic asymmetry coefficient leads to an increase in the tangential contact stresses

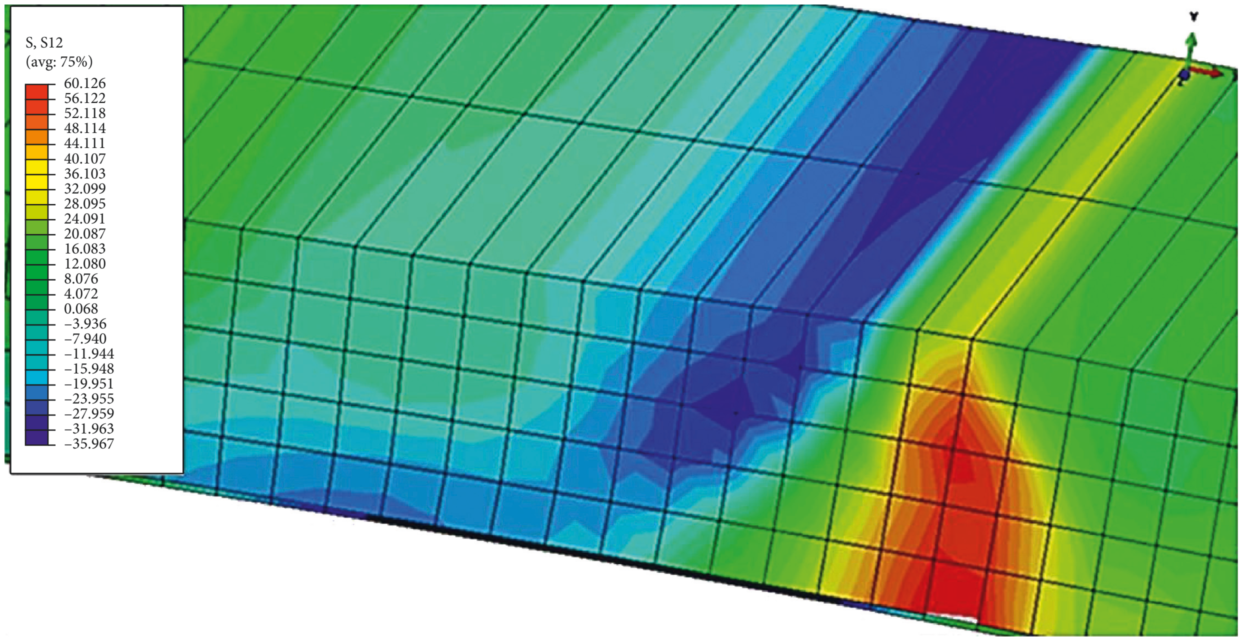

FIGURE 19: The distribution of tangential contact stresses in a thermal deformation hearth at $K_v = 1.075$.

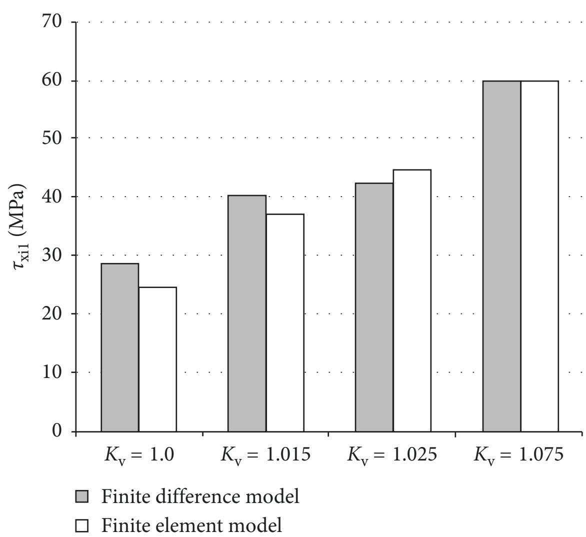

FIGURE 20: Comparative analysis of the calculated values of tangential contact stresses obtained using the proposed finite difference and finite element models.

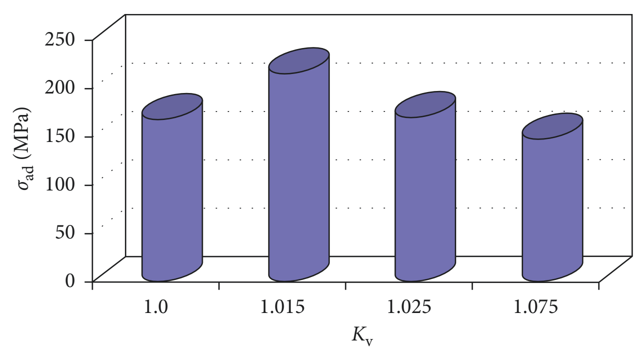

FIGURE 21: The adhesion strength of the welded samples.

in the zone of contact of the electrode tape with the roller electrode. This can contribute to the sticking of the tape on the roller electrode, reducing of the adhesion strength of the coating with part's surface and prevent the formation of high-quality coating.

Thus, in the course of finite element modeling, the data of the finite difference model on the kinematic asymmetry coefficient influence on the change in the local energy-force characteristics of the electrocontact surfacing process by tapes of cylindrical parts are confirmed. It is established that an increase in the adhesion strength of the welded surface is possible due to an increase in the friction coefficient in the zone of their contact, which corresponds with data [24–26]. According to the obtained data, the optimal value of the kinematic asymmetry coefficient is 1.015 with the invariability of the other parameters of the regime. This allows us to increase the adhesion strength of the welded layer and simultaneously avoid the increase of the mechanical and thermal action on the metal of the welded layer and to prevent an increase in the friction coefficient in the contact zone of the electrode material with a roller electrode, which increases the operational stability of the tool.

6. Discussion

According to the data obtained, the heating of the electrode material is initiated in the area of its contact with the surface of the detail. At the same section of the tape, the maximum thermal temperatures are observed in the thermal deformation zone during the whole heating period. The main part of the electrode material in the thermal deformation zone is in the viscous-plastic state caused by heating up to

911–1010°C. Comparison of the modeling results of spatiotemporal thermal fields for different durations of electric current pulse flow indicates the leveling of the temperature gradient in the thermal deformation center, both along the length and width of the tape with increasing time of the current pulse.

In order to study the effect of the electric current pulse duration on the change in the picture of the electrode strip stress-strain state in the thermal deformation zone, a modeling of the process flow was carried out at $K_v = 1.015$ and $K_v = 1.0$. It is established that the maximum equivalent stresses (about 115 MPa) during the whole time of the surfacing current pulse in the thermal deformation heath occur in the zone of electrode tape contact with the surface of the part. High values of equivalent stresses in the deposition zone, which has the highest temperature (1200°C) in the thermal deformation zone, are caused by frictional forces conditioned by the kinematic asymmetry of the electrocontact surfacing process.

A short-term impulse of electric current of 6000 A promotes almost instantaneous heating of the electrode tape in the surfacing zone. The frictional force in the zone of contact of the tape with the surface of the part acting as a result of the kinematic asymmetry does not have a significant effect on the heating of the tape. However, the presence of friction improves the adhesion of the tape to the surface of the part. This contributes to high-quality coating formation.

According to the results of the presented finite element modeling, the deformation processes practically do not occur in the contact zone of the electrode tape with the roller electrode surface: they practically do not change in this contact zone and amount to 0.101. This is caused by the low values of tangential contact stresses (25-26 MPa) typical for this section of the tape thickness and also the relatively low temperature of the material in this zone (900°C). On the contrary, equivalent deformations are characterized by maximum values in the contact zone of the steel tape with the surface of the part (45 MPa). Such a picture is observed with increasing duration of the surfacing current pulse and agrees well with the data of the developed finite element mathematical model of the electrocontact surfacing by tapes [22].

The effect of the kinematic asymmetry coefficient magnitude on the change in tangential contact stresses in the contact area of the electrode material with the surface of the roller electrode and the remanufactured part is analyzed. It is established that an increase in the kinematic asymmetry coefficient up to $K_v = 1.015$ leads to an increase in tangential contact stresses in the contact zone of the electrode material with the surface of the remanufactured part up to 38 MPa. The area of tangential contact stresses also changes: in the zone of the electrode tape contact with the part surface, they occupy a larger area than in the contact zone of the tape with the roller electrode (Figures 16–19).

Experimental studies of the adhesion strength of the parts' surface coated with different values of the kinematic asymmetry coefficient were carried out. The results of the experiments indicate an increase in the adhesion strength of the applied layer up to 217 MPa with an increase in the kinematic asymmetry coefficient up to 1.015.

7. Conclusion

Based on the theoretical analysis of the conditions of the process of electrocontact surfacing with tapes using the finite element method, the influence of the value of the kinematic asymmetry coefficient K_v, determined by the ratio of the linear velocities of the roller electrode and the product, on the local energy-force parameters of the process is investigated. It is shown that, at $K_v = 1.015$, the distribution area and the magnitude of the tangential contact stresses in the fusion zone up to 30 MPa are increased, while the tangential contact stresses in the contact zone with the roller electrode are unchanged, which must be taken into account when designing the technological process of restoring the parts. The effect of K_v on the strength of adhesion of the deposited layer and the surface of the part σ_{ad} is experimentally established: at $K_v = 1.015$, strength of adhesion strength increases by 1.54 times to 217 MPa.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Disclosure

The submission of the authors' paper implies that it has not been previously published, that it is not under consideration for publication elsewhere, and that it will not be published elsewhere in the same form without the written permission of the editors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

All authors participated in the design of this work and performed equally. All authors read and approved the final manuscript.

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