Consider temperature and pressure dependences of the contact area

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Abstract. The dependence of contact as a function of temperature, pressure and microgeometry (roughness) of the surface of the original material, as well as the mechanical properties of the treated surfaces of the parts of road-building machinery and equipment production of building materials, products and structures. The nature of contact interaction of different crystal materials at the thermal strain effect has been discussed. The relationship of the kinetics and character of smoothing microprotrusion and kinetics of contact strength increase in pressure welding at heating has been established. The displacement microprotrusion mechanism for the second stage of the process compared to the first stage has been defined. Linear dimensions the activated surface parts and bundle slip bundle have been found by theory and confirmed by experiment enough reliably. Kinetic dependence of physical contact with the oppositely and dissimilar materials with sharply varying resistance to plastic deformation had been ascertained and determined. The mechanism crumple microprotrusions for the second stage of the process compared to the first stage has been defined. Linear dimensions of the activated surface parts and bundle slip packs have been found by theory and confirmed by experiment enough reliably.

Keywords: physical contact, activation, adhesion, microplastic deformation, stresses of the second kind, slip pack.

1 Introduction

Contact interaction of different materials at the thermal strain effect is of great both scientific and practical interest from standpoint of precise contact of these materials remaining their initial mechanical properties, electrophysical characteristics, etc. On the one hand, to obtain a tough contact, the kinetics and nature of the contact surface processes in pressure welding at heating must be known. Direct experimental data on the kinetics of some process stages are assumed to be available. On the other hand, a precise contact stipulates the control and regulation of plastic deformation of the contact surface microrelief. Therefore, the problem of contact interaction at the thermal strain effect must be discussed on two terms:

- To establish kinetic regularities of the physical contact of surfaces due to microprotrusion smoothing by plastic deformation considering the change of mechanical and

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elastic properties of metals and surface microgeometry [1,2,5,7,11,12]. It allows one to solve the problem of the precise contact [10,14,15].

- To establish the nature of the surface activation by a harder material in contact with a soft metal as well as kinetic regularities of the contact strength increase (adhesion). It permits to work out a problem of a tough contact, e.g. solid state welding.

Notions about three-stage contact interaction of solid materials, in pressure welding at heating including, and kinetics have allowed to construct calculation models for some stages and the process as a whole [1, 2].

Despite of lots of experimental data [6-8] available to date on the contact formation and technological problems on making the contact of specific material pairs, and practical works [3, 4], analyzing some aspects and the problem as a whole, the discussion of this problem is to be continued for the following reasons:

● Experimental and predicted results obtained by equations determining the duration of some process stages have been found to be very different. A general disadvantage of these expressions are volume creep parameters as well as any chosen coefficients changing from 0 to 1. The physical contact formation and activation of the contact surface are known to be found due to plastic deformation of micro protrusions, quality and quantity regularities of which smoothing at the thermal strain effect have not been established yet [6,13,16].

● The works available at present don’t give any experimentally proved methods to determine the physical contact area, under considering the change of mechanical and elastic properties of micro protrusion metals, surface geometry, working contact stresses and contact change character (elastic-plastic to plastic) [5,17-19].

In pressure welding of different materials at heating, the shift of kinetic curves of the physical contact and joint strength increase is observed and must be considered by practical processes [3,20]. The mechanism of such a shift has not been established yet.

In view of the facts mentioned above, the work aim was as follows:

- Based on the results of investigations of the contact interaction of different materials at the thermal strain effect, to establish the main quality and quantity regularities of the physical contact due to smoothing of micro protrusions as well as its relationship with the kinetics of adhesion showing the kinetics of the contact strength increase.

- To clear the shift mechanism of the kinetic curve of adhesion compared to the kinetic curve of the physical contract.

2 Materials and Methods

1. There have been developed the methods to study the kinetics of the physical contact due to plastic deformation of micro protrusions and the character of their smoothing at the thermal strain effect [2,9,10]. The methods are based on a comparison of profilograms for a fixed surface section before and on the pressure effect by help of a plane solid with high creep resistance, hardness and surface purity. As such a material, a synthetic sapphire in the form of a 60° oriented disc and \( R_z = 0.03–0.05 \, \mu \) has been used. For the fixed surface sections, profilograms with the chosen vertical (VM: 1000–100000) and horizontal (HM: 200–4000) magnification were made. Simultaneously, the fixed section was pictured and the width and height of the micro protrusion base measured by the binary microscope MIS-II. Specimen loading was carried out in a special arrangement ensuring uniform heating of the specimen and the pressure transfer. The specimen was placed into a chamber evacuated up to \((1–5) \cdot 10^{-5} \, \text{mm Hg}\) and heated to the working temperature. The experimental study was carried out in the temperature range \((0.01–0.9)T_{\text{melt}}\). External pressure \( P = 5 – 80 \, \text{MPa}\) was applied to the contact surfaces by a sapphire disc. The pressure effect continues for
10 –30 s to dozens of minutes. Metallic surfaces were turned from $R_z = 1.6 – 6.3 \mu$ to $R_z = 40 – 80 \mu$. Before loading, the specimens were annealed in vacuum and electropolished according to standard modes. Experimental study was carried out on material pairs: synthetic monocrystal corundum – copper, $Fe_{50}Ni_{50}$ alloy, titanium, aluminum [3,19-23].

2. To clear the shift mechanism of the kinetic curve for the contact strength increase compared to the kinetic curve of the physical contact, there has been developed the calculation method for the second kind, stresses, occurring at plastic deformation of the surface layer of metal grains as well as the method to determine the linear sizes of activated surface sections due to a slip pack.

3. Results

For technological reasons, the welding pressure is chosen to ensure optimum residual deformation of the products, e. g. the pressure value mustn’t be higher than that of the yield strength of materials with the minimum strength at the welding temperature. Therefore, the contact is assumed to be elastic-plastic, e. g. plastic deformed are mainly the micro-protrusions, but the waves are elastic deformed. According to [7], the relative contour area $S_c$ may be calculated for such a contact by the equation:

$$S_c = \frac{P}{HV} \cdot S,$$

(1)

where: $P$ is pressure, $HV$ is hardness, $S$ is actual contact area or that of the physical contact. On the other hand, at the normal height distribution of micro-protrusions at

$$\bar{S} = b \cdot \varepsilon^v,$$

(2)

where: $b$ and $v$ are equal to 2 [7]; and $\varepsilon$ is relative rapprochement; contour pressure $P_c$ may be determined by the formula

$$P_c = a \cdot E^{0.8} \cdot \beta^{0.4} \cdot P^{0.2}$$

(3)

where $P$ is nominal pressure; $a = 0.2$ and 0.5 for cylindrical and spherical waviness, respectively; $\beta$ – value is in the range $10^{-4}$ to $10^{-6}$ determining the ratio height $R_z$/radius and depending on the surface purity. The higher $\beta$ – value corresponds to a rough surface, the lower one to the fine turned surface. On the other hand, contour pressure value $P$ is equal to the ratio pressure/contour contact area, e. g.

$$P_c = \frac{P}{S_c}$$

(4)

At the substitution of Eq. (4) into Eq. (3), one can obtain $S_c$, and equating with Eq. (1),

$$P / HV \cdot S = a^{-1} \cdot \beta^{-0.4} \cdot (P / E)^{0.8}$$

(5)

Note that Eq. (3) was repeatedly controlled by the contact surface of various size and purity being assumed satisfactory for engineering, for example, in [7]. Taking logarithms of Eq. (5), all the experimental data on the kinetics of the physical contact area depending upon the working parameters of smoothing or welding may be assumed to be grouping in logarithmic coordinates $\ln (P / HV \cdot S) – \ln (P/E)$ along the straight line which slope tangent to axis $P/E$ is about 0,8 Fig. 1a displays Eq. (5) being well fulfilled at the time corresponding to the loading period (30 s) by turned and planed surfaces. The 15% – confidence interval including the majority of experimental points (> 90%) is given by dotted lines. No regularity of the point locations at different temperatures is observed. Out of this interval are the points determined at low temperatures (< 373 K). For the calculations, we have used $HV$ 400 MPa [6,7]. But actual $HV$ values are somewhat higher and equal to about 500 MPa according to our investigations carried out on the specimens being used in experiment. Are used our experimental values for hardness [3], all the experimental points on the physical contact surface are in the 15% – confidence interval.

In low strength and temperature (< 373 K) ranges, a systematic deviation of parameter $P/HV \cdot S$ for a decrease ($S$ increase) is observed. The value of the contact pressure in this range isn’t higher than that of the elastic strength of a compact material. Assumed may be an
increase of the contact area and deviation from Eq. (5) caused by plastic smoothing of the maximum micro-protrusion peak (the first stage of micro-protrusion smoothing) while lots of them are in elastic state, e. g. the contact strain conditions are different from those of Eq. (5). At the decrease of parameter $P/HV \cdot S$ corresponding to $S$ increase, the deviations are observed even at high $P/E$ values by $P/HVS \approx 1$. It is evident that these deviations depend on the wave transfer into the plastic state. The same data are given in Fig. 1b for 5 min. contact. These results are shown to confirm the facts mentioned above.

Fig. 2 a, b display the experimental results of the physical contact area for the whole period of time (0.5...34.5 min.), pressure $P = 5...80$ MPa and temperature under Investigation. According to the present results, the regularity of Eq. (5) is shown to be found in the whole temperature range (293–973 K). The temperature dependence of parameter $P/HV \cdot S$ and that of $\bar{S}$ is determined by the temperature dependence $HV$/strength properties and elastic modulus ($E$), e. g. the following expression

$$\bar{S}(T) - E(T)^{0.8}/HV(T)$$  \hspace{0.5cm} (6)

As shown by the temperature dependence of parameters $E^{0.8}/HV$ for copper and $\ln (E^{0.8}/HV)$ on $T$ and $1/T$ given in Fig. 2, it is found to be non-linear (curve 1) but well rectified in coordinates $\ln (E^{0.8}/HV) - T$ (curve 2) and $\ln (E^{0.8}/HV) - 1/T$ (curve 3) forming two straight line sections: up to 700...750 K and above. Eq. (5) is fulfilled also for surfaces turned at $R_z = 3.2 – 6.3 \mu$ in the whole temperature and pressure range.

So, two types of experimental dependence of $S$ upon $T$ may be in fact fulfilled. Being the result of temperature dependence of two parameters $E^{0.8}/HV$ characterizing strength ($HV$) and elastic ($E$) properties of metals, conventional methods used to control the temperature dependence of S are unlikely strong, and the literature data must be carefully interpreted according to the relationship being similar to that of Eq. (5).
Fig. 1. The relationship of parameters \((P/HV \cdot S) - (P/E)\) at the physical contact formation by a pair copper-sapphire in the temperature range 293–1173 K at \(t = 0.5\) min (a) and 5.5 min (b).

Fig. 2. The relationship of parameters \((P/HV \cdot S) - (P/E)\) at the physical contact formation by a pair copper-sapphire at 673 K (a), 973 K (b) for 0.5–34.5 min. 1 – 0.5 min, 2 – 2.5 min, 3 – 3.5 min, 4 – 9.5 min, 5 – 14.5 min, 6 – 19.5 min, 7 – 24.4 min, 8 – 34.5 min.

For instance, consider the relationship of the type
\[ S = K \left( e^{Q/RT} \cdot t \right)^n \]  
examined by Mulheran and Tabor [6, 8] for lead and indium at high homological temperatures but at stresses of a single contact. Here \(K\) is coefficient depending on pressure, load and indenter diameter; \(Q\) is creep activation energy, other symbols being clear from designations given earlier. Taking logarithms of Eq. (7), the expression
\[ \ln S \approx n Q/RT \]  
is obtained. If \(S = HV/E^{0.8}\), then the in \((HV/E^{0.8})\) slope to axis 1/T (Fig. 3, curve 3) determines the value for \(n Q/R\). Taking into account by copper “n”
from Eq. (7) being equal to 0.1–0.01, one can determine the value for $Q$ corresponding to the creep activation energy. According to own data, the effective activation energy ($n \cdot Q$) is equal to about 20 kJ/mol. As summing $n \approx 0.07$, one can obtain $Q \approx 300$ kJ/mol being in agreement with the activation energy of high temperature creep of copper [9,10].

3.1. Consider time dependence of the contact area

To clear this regularity, the time dependence of parameters under study is usually constructed in binary logarithmic coordinates. But the starting moment of the physical contact formation (loading period), which formation intensity may differ from that of its development on the next stages sufficiently is left out of account. At the first moments of load application, the contact microprotrusion deform by a mode more similar to uniform loading than to creep at which the contact, develops on finishing of active deformation. Evidently, only suggests to take into account this fact using the term “prolonged” time $t_o$. Otherwise, the dependence $f(t + t_o)$ is suggested instead of $f(t)$ thus translating the origin of time coordinates to $t_o$. But in our opinion, such a method has at least two disadvantages:

1. A difficult determination of $t$ being possible at the given dependence $f(t)$ only.
2. An impossible control of the analytical prolongation of the curve $f(t)$ towards negative time of an actual starting event from standpoint of physics of the phenomenon as a whole.

Schematically, the curve construction by a displacement of the origin of coordinates to that of the curve along the axis of ordinates is considered to be equal in rights mathematically. This method is assumed to be more acceptable in our case, being independent on labour-consuming control of the reading point in shift.

According to Eq. (5), the intersection point of (Fig. 1) with abscissa axis must determine the coefficient $\alpha^{-1} \beta^{0.4}$. But this relation has been found at leaving the time factor out of account or assuming non-evident agreement between time (30 s) and loading period. Therefore, according to Eq. (5) and comparison of Figs. 1 and 2 (the intersection point with abscissa), the coefficient dimension of the right member (Eq.5) must include the time factor too. Then the time dependence of this coefficient must be as follows:
\[ K(t) = \alpha^{-1} \cdot \beta^{-0.4} \cdot f(t_0/t) \]  
(9)

Parameter \( t_0 \) is easily determined by using the data of Figs. 1 and 2, if the parameters of waviness, e.g., \( \beta \) coefficient and \( \alpha \) – waviness, have been exactly defined. Table 1 shows the data on the waviness determined in a series of investigations [10].

<table>
<thead>
<tr>
<th>Method of treatment</th>
<th>Purity class</th>
<th>Micro-protrusion height roughness</th>
<th>waviness</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>4</td>
<td>44</td>
<td>12</td>
<td>6 \cdot 10^{-4}</td>
</tr>
<tr>
<td>Fine burning</td>
<td>8</td>
<td>3.4</td>
<td>2</td>
<td>3.6 \cdot 10^{-5}</td>
</tr>
</tbody>
</table>

To determine the area of the physical contact at a tentative finishing of active deformation, the time dependence of parameter \( P/HV \cdot S(E/P)^{0.8} \) (curve 1 at \( R = 3.2–6.3 \mu \); curve 2 at \( R = 40–80 \mu \)) is plotted in Fig. 3 with a logarithmic accuracy, e.g., \( \ln (\bar{S} \cdot HV/P^{0.2} \cdot E^{0.8}) + 15\% \) for both curves.

Transforming into absolute accuracy, one can obtain for the curve at \( R_z = 2–5 \mu \) and \( t \approx 2 \) min.

\[ 3.18 \cdot 10^{-3} - 6.74 \cdot 10^{-3} - 1.4 \cdot 10^{-2}, \quad \text{e.g.,} \approx 50\%. \]

According to Fig. 4a, the welding time increase above 15–20 and 20–25 min, by rough and fine treatment, respectively, is low-effective because area of the physical contact doesn’t increase at this time. Although the time dependence \( t^0 \) and \( S \) increases with the time infinitely, limiting parameters at the time mentioned above

\[ \bar{S} \cdot HV/P^{0.2} \cdot E^{0.8} \quad \text{and} \quad \bar{S} \cdot HV/P^{0.3} \cdot E^{0.7} \]  
(10)

may be assumed to be equal to about \( 5.10^{-3} \) and \( (1.35...1.4) \cdot 10^{-2} \) by rough and fine treatment, respectively. Their starting or instantaneous values are \( (2.2–2.4) \cdot 10^{-3} \) and \( 5 \cdot 10^{-3} \) respectively.

Of interest is the value for \( S \) determined in loading from Eq. (10), e.g.,

\[ \bar{S} \approx (P^{0.3} \cdot E^{0.7}) / EV \cdot (1.4 \cdot 10^2) \]  
(11)

1. Assume \( P = 5 \text{ MPa} \) and \( T = 1073 \text{ K} \). Then we have:
   calculated: \( \bar{S} \approx 75\% \) but \( \bar{S}_{\text{inst}} \approx 27\% \)
   experimental: \( \bar{S} \approx 84\% \) but \( \bar{S}_{\text{inst}} \approx 29\% \).
2. Assume \( P = 5 \text{ MPa} \) and \( T = 973 \text{ K} \). Then we have:
   calculated: \( \bar{S} \approx 59\% \) but \( \bar{S}_{\text{inst}} \approx 22\% \)
   experimental: \( \bar{S} \approx 65\% \) but \( \bar{S}_{\text{inst}} \approx 24\% \).

Calculated and experimental results are observed to be in agreement.

According to [6–8], waviness parameter \( \beta \) of the surface planed is in the range \( 6 \cdot 10^{-4} \) to \( 3 \cdot 10^{-3} \); and turned – \( 10^{-5} \). Then \( \alpha \cdot \beta^{0.4} \) must be about \( (2–5) \cdot 10^{-3} \) for the surface at \( R_z = 40–80 \mu \) and \( 10^2 \) at \( R_z = 2–6 \mu \). Parameter \( \alpha \cdot \beta^{0.4} \) of the surface at \( R_z = 40–80 \mu \) is about \( (2.2–2.4) \cdot 10^{-3} \) on loading according to Fig. 4a, and experimental results by other authors. At \( R_z = 2–6 \mu \), the value for parameter \( \alpha \cdot \beta^{0.4} \) is about \( 5 \cdot 10^{-3} \) being somewhat lower than those given by other authors. Obviously, it depends on some methodical discrepancies in experiments, namely small diameter of the specimens under investigation. The range of by literature recommended values for coefficient \( \beta \) at \( \alpha = 0.5 \) (spherical waviness) is given on the axis of ordinates by dotted line. The origin of the curves is in this range. Therefore, the relative area of the physical contact in loading (or active deformation) may be calculated by Eq. (5) with an accuracy being acceptable for engineering [10].
Based on the facts mentioned above, generalized Eq. (5) taking into account time factor may be written as follows:

\[ \frac{P}{HV \cdot S} - \frac{P}{HV \cdot S_0} = K(t) \cdot \left( \frac{P}{E} \right)^{0,8} \]  

(12)

The dependence \( K(t) \) may be assumed to be the power one. Taking logarithms by Eq. (12) and constructing a diagram, coefficients of the time dependence (Fig. 7b) may be determined. In both cases, experimental points are shown to be arranged on straight lines at the axis slope \(-0.54\) (straight line 1, turning) and \(0.2\) (straight line 2, planning). There are two process stages by rough surfaces at \( n_1 = 0.5 \) for \( t < 2.5 \) min. and \( n_2 = 0.2 \) for \( t > 2.5 \) min. being not observed at low \( R_z \). Obviously, the reason is that the contact surfaces are as if drowned in the micro-protrusion base at the first moments and on smoothing or rough surfaces because of strain hardening of micro-protrusions. It is also one of the reasons why metals of the micro-protrusion contact surfaces don’t creep over the response surface or activate the latter.

To the contrary, at low \( R_z \) micro-protrusions reach the third stage of smoothing and become as if crawled over the response surface of a harder material, e.g. micro-protrusion metals of the contact surfaces flow and ensure the activation of the response surface of a harder material. This phenomenon explains the fact observed in practice, the \((6–8)th\) class being optimum for the surface purity in pressure welding at heating and \( R_z = 1.6–10 \) \( \mu \). As very smooth surfaces don’t cause crawling and smoothing of micro-protrusions as well as metal creeping over the response surface depending on the change of the contact character mentioned above, the formation of an almost perfect physical contact is finished due to high temperature volume creep and sintering.

![Diagram](image1)

![Diagram](image2)
Based on the study carried out, the final expression to determine the area of the physical contact $\bar{S}$ is:

$$\bar{S}(t) = (\alpha \cdot \beta^{0.4}) \cdot \frac{P}{HV} \cdot \left(\frac{E}{P}\right)^m \left[1 - \left(\frac{t_o}{t}\right)^n\right],$$  \hspace{1cm} (13)

where: $\alpha$ and $\beta$ are coefficients determined by microgeometric parameters of the contact surface; $HV$ is metal hardness; $m$ and $n$ are parameters depended upon the surface purity ($R_z$) and equal to $m = 0.8$ and $n = 0.2$ at $R_z = 40 - 80 \mu$ and $m = 0.7$ and $n = 0.54$ at $R_z = 3.2 - 6.3 \mu$;

$P$ is nominal pressure, $E$ is elastic modulus, $t_o$ - parameter of time considered for a loading period and chosen in experiment at $\alpha$ and $\beta$ parameters known, $t$ is current time.

The analysis of the most experimental results (Fig. 4b) on the physical contact area in the whole temperature and pressure range under investigations, has shown the relationship between experimental parameters $m$, $n$, $S_o$ and the points determined in a direct experiment to be good correlated. The main parameters affecting the intensity (rate) of the physical contact formation are $n$ and $t$. Parameter $n$ depends on the surface purity sufficiently, e. g. on $R_z$. Quality and quantity regularities of the physical contact formation due to smoothing of micro-protrusions being studied on different material pairs with strong different physicochemical properties in the temperature range of metals 0.01 to 0.9/$T_{\text{melt}}$ and pressure range 5 to 80 MPa have allowed one to establish that: physical contact area formed by different materials with strong different resistivity to plastic deformation due to smoothing of micro-protrusion metals depends on geometric surface characteristics $R_z$, $\alpha$ and $\beta$, mechanical and elastic properties of metals (by $HV$ and $E$, respectively) and may be expressed as follows:

$$\bar{S}(t) = S_o [1 - \left(\frac{t_o}{t}\right)^n],$$  \hspace{1cm} (14)

where: $S_o$ is initial contact area formed in loading and equal to:

$$S_o = \alpha \cdot \beta^{0.4} \cdot \frac{P}{HV} \cdot \left(\frac{E}{P}\right)^m.$$

4 Discussion

The results of measuring the hardness of the metal on the surface of the contact pads and along the height of the microprotrusions suggest that at a low temperature of contact interaction under pressure (293–773 K), significant strain hardening is observed (by a factor of 1.6–2.4). In this case, the highest degree of hardening corresponds to the period of unsteady creep (time less than 2.5 min) and after its completion, the hardness values stabilize and remain constant. This nature of its change confirms the previously established regularities in the development of physical contact due to the collapse of microprotrusions. In the noted temperature range, physical contact is formed at a low and constant speed, without reaching the 2nd stage of microprotrusion collapse (3rd and 4th stages of microprotrusion collapse) and does not provide conditions for relay-race transfer of deformation and its development in a harder material [19]. The consequence of this is the absence of connection (activation of the response surface and setting), i. e., the process of contact interaction stops at the stage of formation of physical contact.
At a process temperature of more than 0.5 $T_{\text{melt}}$ of the metal, the hardening of the surface of the contact pads and the near-contact volume is replaced by softening by -30%. It proceeds most intensively in the first minutes of the process. With an increase in $T$, this period and the time to reach the 2nd stage of microprotrusion collapse decrease. In all cases, the depth of the layer with the hardness changed as a result of deformation does not exceed the surface roughness parameter. With regard to the development of schemes for calculating the duration of the first stage of the process, this confirms the validity of the statement about the need to consider the base of the microprotrusion as rigid. The established nature of the change in hardness, which reflects changes in mechanical properties, is in good agreement with the data obtained on the effect of temperature on the rate of formation of physical contact as a result of plastic deformation of microprotrusions.

On surfaces with low values of the roughness parameter $R_z$, the processing microprotrusions quickly reach the 2nd stage of collapse (the 3rd and 4th stages of collapse) of the microprotrusions and begin, as it were, to spread over the mating surface of a harder material, i.e., the metal of the contact pads of the microprotrusions flows and this, on the one hand, maintains the activity of its own surface, on the other hand, it contributes to the occurrence of plastic deformation in the near-contact volumes of a harder material and its activation according to the mechanism proposed in [19]. This explains the fact observed in practice that the optimal method of surface treatment for pressure welding with heating is finishing turning with $R_z = 1.6 - 10 \, \mu m$ [17]. Since on smooth surfaces with a small value of $R_z$ (less than 1.0 \, \mu m), there is almost no spreading and flow of metal on the contact pads of microprotrusions (this is due to a change in the nature of the contact), in this case the formation of complete physical contact ends due to volume metal creep and accompanying diffusion processes.

Based on the analysis carried out, we obtain the final expression for determining the area of physical contact (formulas 14 and 15), where $m$ and $n$ are coefficients depending on the surface roughness; at $R_z = 40 - 80 \, \mu m$ $m = 0.8$, $n = 0.2$; at $R_z = 3.2 - 6.3 \, \mu m$ $m = 0.7$, $n = 0.54$; $t$ is the current time. As can be seen from fig. 4, the experimental data on the area of physical contact in the entire studied temperature and pressure range and the graphical dependence constructed from the experimental values of the parameters $m$, $g$, $b$, $S_o$ correlate well with each other. The main parameter affecting the rate of contact formation is the index $n$ at $t$, which largely depends on the roughness of the surface treatment.

5 Conclusion

1. It has been established that at the contact interaction of different crystal materials with the highly different resistance to the plastic deformation and nature of chemical bonds under pressure at heating the smoothing of micro-protrusions occurs in two stages: 1 – before plastic flow of metals over the contact surfaces and 2 – on starting of visible metal flow over the surface of the contact sections. The stages of the micro-protrusion smoothing affect the kinetics of adhesion in the contact spot sufficiently. Depending on the thermal strain effect, the development of the physical contact is finished on different stages of micro-protrusion smoothing. If the development of the physical contact finished on the first stage, that adhesion is observed (at macro-scale), but the process of a fine treatment by smoothing takes place. Adhesion is observed, if the physical contact development is finished on the second stage.

2. It has been established that the kinetic curves of adhesion (strength increase) are of the sigma type with the displacement period of the second stage relative to the first one. The period of this displacement is determined by starting of a marked metal flow over the micro-protrusion contact sections and its passing on the baton into a harder material under the second kind stresses. The second kind stresses are higher than the necessary punching stress minimum of a harder material ensuring plastic deformation of the latter.
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