CONSTRUCTION OF KINETIC CURVES OF CONTACT FORMATION BY CRUSHING MICROASPERITIES IN CONTACT BETWEEN DISSIMILAR MATERIALS UNDER THERMOFORMING IMPACT USING ARTIFICIAL INTELLIGENCE METHODS

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Abstract

An analysis of the formation of true contact (which, under certain temperature and pressure conditions, transitions into physical contact) between dissimilar crystalline materials with markedly different physico-mechanical properties has been carried out using the copper–corundum contact pair as an example. The applicability of artificial intelligence methods for modeling the kinetics of true contact formation and microasperity deformation is examined. An algorithm for constructing kinetic curves of contact formation between dissimilar materials using artificial intelligence methods over a wide range of temperatures and pressures has been developed. In the future, this algorithm may serve as the basis for an automated system for controlling the technological process of producing precision detachable and non-detachable joints and high-purity metallic surfaces with controllable and adjustable mechanical properties, free of foreign particles on the surface and in the near-contact volume.

Keywords: kinetic dependencies, true contact, physical contact, precision detachable and non-detachable joints, artificial intelligence, copper, corundum, thermoforming impact, microasperity.

At the current stage of development of engineering and technology, many design and technological solutions are based on solid-phase contact interaction under various types of thermoforming impact. A special place among these is occupied by technological processes based on plastic deformation of contact surfaces (pressure welding with heating, pressing and sintering of high-dispersion powders, production of metal nanoparticles from decomposition of metal–organic crystalline salts followed by welding of compact materials, all types of blade and diamond machining of metallic surfaces with adjustable mechanical properties, production of high-purity metallic surfaces with adjustable and controllable mechanical properties on the surface and in the near-contact volume free of foreign inclusions, etc.) with subsequent relaxation processes. In this case, maximum preservation of the complex of initial material properties of the assembly components is ensured, together with effective process control and regulation of the degree of contact precision.

According to modern concepts, the contact interaction of materials under thermoforming impact belongs to the class of solid-phase topochemical reactions [1–3] and proceeds in three main stages: (1) formation of physical contact; (2) activation of atoms at the contact surfaces and formation of strong chemical (metallic) bonds; (3) relaxation stage (diffusion processes, recrystallization, formation of common grains, etc.). Physical contact is understood as the approach of atoms of the contacting surfaces to a distance at which exchange processes of electron interaction become possible, i.e., to a distance of the crystal lattice parameter. This means that between the contacting surfaces during the formation of a non-detachable joint (seizure), there must be no inclusions (contaminants), not even a complex of physical and chemical adsorption. For the production of a detachable precision joint (producing high-purity metallic surfaces), this condition is not mandatory.

Since the formation of physical contact is preceded by the formation of true contact through plastic deformation of the machining micro-irregularities (microasperities) of the contacting surfaces, as well as activation of the contact surfaces and seizure, the relevance of this study is self-evident.

At present, one of the most pressing tasks is the production of high-purity precision metallic surfaces used in high-technology industries such as mechanical engineering, electronics, etc., as well as the production of reliable welded joints in metallic structures.

On kinetic curves of contact formation, three stages characteristic of a creep kinetic curve can be identified: the period of active deformation (loading period), during which intensive growth of the contact area occurs; the period of non-steady-state creep — a transitional zone characterized by a gradual change (decrease) in the deformation rate and contact area, and redistribution of contact zones; and the period of steady-state creep, when the process reaches a stable state (constant rate) [4–6].

Experimental studies of the effect of the thermoforming impact level on the kinetics of crushing and deformation of microasperities of the contacting surfaces were carried out on a copper MB–corundum pair over a wide range of temperatures and pressures; the copper contact surface was prepared by planing with R_z = 40–80 μm according to the method in [4].

Based on available experimental data on contact area S, % versus time t, s at various levels of thermoforming impact, dependencies of contact area formation on time were obtained for the active deformation stage and the steady-state creep stage in the contact of dissimilar materials with markedly different resistance to plastic deformation (using the copper–corundum pair as an example).

The obtained dependencies obey the following law:

$$S = a + b\ln(t'), \qquad (1)$$

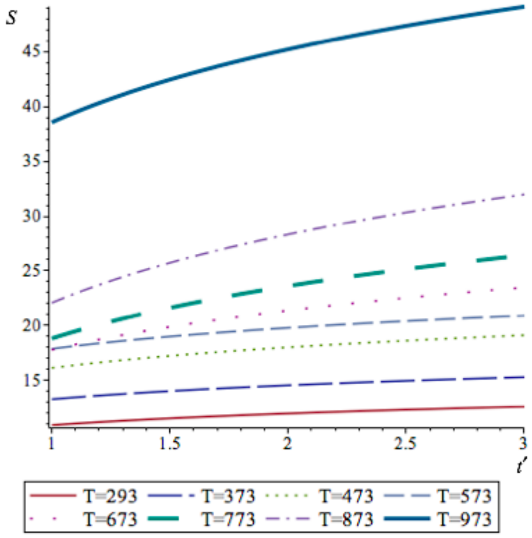
where $t' = t/10$; where 10 s corresponds to the onset time of true contact formation.

The coefficients *a* and *b* in equation (1) were determined according to the formulae:

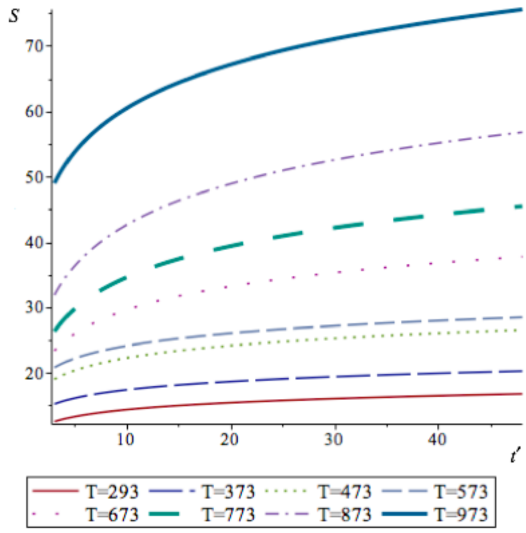
$$a = \overline{S} - b\overline{X},\ b = \frac{\overline{SX} - \overline{S}\cdot\overline{X}}{\overline{X^2} - \left(\overline{X}\right)^2}, \qquad (2)$$

where $X = \ln(t')$. Overbans in formulae (2) denote mean values of the corresponding quantities.

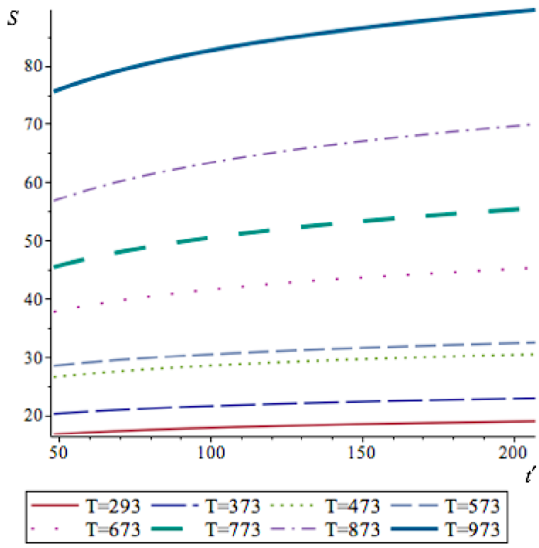
For nominal pressure $\sigma_н$ = 30 MPa and temperatures T= 293 K, 373 K, 473 K, 573 K, 673 K, 773 K, 873 K, 973 K, the resulting dependencies *S(t')* are presented in Fig. 1 (a, b, c).



a — active deformation period, t = 10–30 s



b — non-steady-state creep period, t = 30–480 s



c — steady-state creep period, t = 480–2070 s

Fig.1. Kinetics of contact formation at $\sigma_н$ *= 30 MPa:*
a — active deformation period (t = 10–30 s); b — non-steady-state creep period (t = 30–480 s);
c — steady-state creep period (t = 480–2070 s).
Studies on microhardness changes are presented in Figure 2.

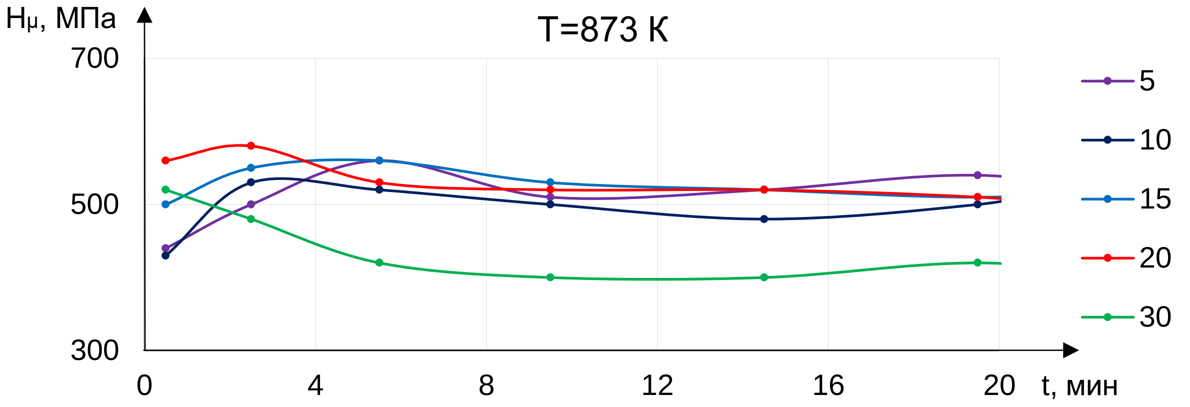


Fig. 2. Change in microhardness at the surface of microasperity contact pads under nominal pressure ($\sigma_н$ = 5…30 MPa) and temperature T =873 K.

These curves fully confirm the progression of the kinetic curves of true (physical) contact formation at the stages of active deformation, non-steady-state creep, and steady-state creep.

To determine the kinetic dependencies over a wide range of temperatures, pressures, and microasperity heights, artificial intelligence methods may be applied. To this end, augmentation of the available experimental data should be carried out using Python libraries to implement the computational algorithm.

For processing and analyzing experimental data, the NumPy and pandas libraries may be used to form arrays *S(t')* and to structure samples by temperature and pressure parameters.

For building regression and neural network models, the scikit-learn library is used; if more refined description of the already established dependencies of contact area on temperature, pressure, and microasperity height over time is required, the PyTorch or TensorFlow/Keras libraries may be applied, enabling neural networks of various architectures and improving the accuracy of kinetic dependency approximation.

Construction of new kinetic curves outside the ranges covered by the experimental data is carried out using the SciPy package.

For visualization of results and construction of the final kinetic curves *S(t')* over the entire time range, the Matplotlib library is used.

The algorithm for constructing kinetic curves of true contact formation may include the following steps:

1. Data preparation. Arrays of experimental values *S(t')* are formed for the active deformation zone (10–30 s), non-steady-state creep (30–480 s), and steady-state creep (480–2070 s).

2. Data augmentation. Interpolation and generation of additional points are performed with account of physical constraints — monotonic growth and continuity of the function.

3. Model construction and training. Based on known experimental dependencies of contact area on temperature, pressure, and microasperity height over time, a regression or neural network model is constructed that provides the dependency $S=f(t, T, \sigma_н, R_z)$. For moderate nonlinearity, regression approximation is used (linear, polynomial, or gradient boosting); for pronounced nonlinearity — a feedforward neural network (PyTorch or TensorFlow/Keras).

4. Using optimization methods (scipy.optimize module), the minimum discrepancy between the model dependency (constructed by artificial intelligence methods) and the experimental dependency derived from experimental data is determined.

5. Construction of the resultant curve. Based on the trained model, the kinetic dependency *S(t')* is formed over the considered range of temperatures and pressures.

The presented algorithm may in the future serve as the basis for developing an automated system capable of performing numerical simulation of the stages of microasperity crushing, its staged nature, and forecasting the development of true (physical) contact between dissimilar materials at various levels of thermoforming impact. Implementation of this approach will allow optimization of the technological processes for producing precision detachable and non-detachable joints with controllable and adjustable mechanical properties on the surface and in the near-contact volume. A separate publication will be dedicated to solving this problem.

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