



Development of devices for measuring contact friction forces in the processes of volumetric plastic deformation

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Abstract

Methods and means for studying the factor of plastic contact friction in the processes of volumetric plastic deformation of solid and hollow precision workpieces were discussed in the article. Estimation of the forces values required for overcoming friction resistance is important for the correct calculation and choice of technological variants for deformation processes, for assessing the properties of technological lubricants, as well as for the correct setting of initial conditions when simulating forming processes using various methods, including using FEM. An analysis of methods and means for assessing the conditions of contact friction in die forming processes was carried out, and a conclusion about the advantage of methods for directly measuring of friction forces in plastic deformation processes compared to ones for indirectly determining friction constants using deformation, kinematic, and force parameters was made. Designs of devices for measuring friction forces directly during the process of plastic deformation have been proposed and tested. Radial extrusion schemes have the advantages of identifying surfaces of directional influence by friction forces and recording them. Based on the results of measurements of friction forces, the effectiveness of several technological lubricants for cold and semi-hot extrusion of steel and aluminum alloys was assessed. The values of friction coefficients according to Siebel's law have been refined. A correlation between friction stress and normalized pressure of extrusion was proposed, in which the flow stress of the near-contact metal layer was expressed through hardness indicators, and correction coefficients were found from experimental data of measuring friction forces. The proposed devices made it possible to expand the understanding of the contact friction factor in the processes of working by pressure, which is important for practice and for plastic deformation processes simulation.

Keywords Plastic deformation process · Contact friction force · Extrusion · Friction force meter · Specific friction force · Friction coefficient

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1 Introduction

In modern conditions, the mechanical engineering industry plays a key role in ensuring economic development. Recently, resource-saving and environmentally friendly metal forming processes, based, among other things, on cold plastic deformation, have become increasingly widespread [1, 2]. Precision volumetric die-forming processes by extrusion are characterized by high contact pressures, the renewals of the workpiece surface, and the sliding speeds of the deformed metal. In this case, the proportion of non-free, i.e., workpiece surfaces in contact with the tool, is very significant, which determines the dependence of the type of stress-strain state, the nature of filling the cavity or outflow of metal, as well as the formation of the structure and surface of products on the conditions of contact friction [3, 4].

Knowledge of the conditions of contact friction is necessary for the correct calculation and selection of technological variants for deformation processes, for assessing the properties of technological lubricants and tool life, and for predicting the quality of parts.

It is also of interest that experimental work on the formulation of friction conditions lags behind the creation of methods for solving boundary value problems in the theory of metalworking processes under pressure [1]. It should also be noted that, despite the complexity of determining and setting the conditions of contact friction, the use of friction for technological purposes has become one of the effective directions for intensifying the processes of volumetric plastic deformation [1, 3].

2 Methods for evaluation of friction conditions in volumetric metal forming

There are many methods for studying the friction factor in the processes of metalworking under pressure, which are divided into methods for indirectly determining friction constants [5, 6], friction simulation on special devices [7], and studying friction forces directly in the deformation processes themselves [8, 9]. The most reliable data in terms of their physical essence are obtained by studying friction directly in the technological process [10].

Methods for studying contact friction can be divided according to the operating principle and the final result into several characteristic groups.

Group 1 includes the simplest indirect methods for assessing the conditions of contact interaction between the deformed metal and the tool. A qualitative assessment of the conditions at the contact is carried out by determining

the forces of deformation or pushing and comparing indicators of deviation of the shape of parts, changes in dividing grids, hardness, macrostructure, or surface roughness [8, 11]. The methods are used to determine the effectiveness of technological lubricants by comparing the values of force or deformation parameters depending on the intensity of friction. Based on the results of measuring the parameters, some indicators of friction conditions can be calculated [9]. The method of cylindrical specimens upsetting with conical grooves using strikers with conical protrusions has found widespread use. By varying the angle of the protrusions, the case of upsetting without the formation of a barrel-shaped surface of the specimen is found [11]. Among the new developments, one can also distinguish the methods of testing for upsetting, for which the absence of the need to measure deformation forces is seen by the authors as their advantages [5].

The methods that make up group 2 can be considered the most long-time and well-known ones [1, 6, 11]. They are identified according to a characteristic feature—the preliminary setting energy-power parameters (forces or deformation pressures) of the process under study (upsetting, extrusion, drawing). Assuming that the approximate calculation formula for the deformation forces is valid, this formula is transformed and solved relative to the friction constants. Thus, contact friction forces are found by measuring the deformation force and using the conditions of the equilibrium state of the element.

Among the new works, one can distinguish methods based on the use of force parameters of extrusion processes [11]. For the forward extrusion process in a conical die, based on plasticity theory, quantitative correlations between the load, friction coefficient, and yield stress of the workpiece material have been defined, and a procedure for testing friction parameters has been developed [12].

The work [13] proposed a method for estimating the value of the friction coefficient in deformation using the backward extrusion method. As a measure of calibration of the friction coefficient, the force parameters are used, which depend on the thickness of the bottom of the extruded cup.

The authors of [14] developed a new test based on the process of back extrusion of a rotating workpiece, which simulates friction during cold deformation. In the analytical model, the friction stress is determined from the measured torque in combination with a finite element method analysis of the sliding speed of the workpiece metal on the punch.

Group 2 methods are characterized by limitations associated with the assumptions made when solving problems about deformation forces. Determining average friction coefficients from experimental data of force parameters has disadvantages caused by the hypothetical nature of the theoretical solutions used.

The analysis of methods included in groups 1 and 2 is described in detail in [6, 9]. Therefore, we will consider the methods without describing the features of possible variants.

Indirect methods for determining friction constants, included in group 3, are based on the experimental determination of some kinematic or deformation parameters of deformation processes and using dependencies between these parameters and friction constants. Various experimental methods are used to deform specimens of various configurations, including, among other things, tests according to the following schemes: ring compression, contour upsetting, extrusion of hollow parts, combined extrusion, and deformation of T-shaped workpieces.

The ring compression test is widely accepted as a method for simply and reliably determining the coefficient of friction during plastic deformation. Its methodology is based on the use of geometric changes in ring diameters [15]. It was proposed in [16] to deform the ring with a boss on the outer rim as a development of the method and to eliminate errors in the results of friction assessment due to unstable changes in diametrical dimensions.

A new open backward extrusion test method was proposed in [17], i.e., using the scheme of contour upsetting of the disk, as an alternative to the ring compression test and to increase the level of operating pressures during testing. At the same time, a finite element model is used to obtain calibration friction curves under conditions of large deformations. In this test, as in the ring compression one, the ends of a cylindrical specimen are in contact with the tool under conditions that differ from those on cylindrical surfaces. In this test, the height of the extruded ledge does not always decrease monotonically with worsening friction conditions, and the influence of the tool geometry on this change is significant and requires a critical assessment of its design [18].

In [19], several experimental methods for determining the friction coefficient in cold deformation were used to obtain friction characteristics. Among them, the most notable ones are the ring compression test, forward extrusion, double extrusion of the cup, upsetting-sliding test, and contour upsetting test. At the same time, quantitative indicators for assessing friction conditions in cold deformation are defined by numerical simulation.

A comparison of different methods for indirect analysis of friction conditions using FEM is also given in [20]. It is noted that the use of the method of upsetting a ring specimen and the method of extrusion of a double-sided cup to study contact friction at hot deforming temperatures is difficult.

New friction test methods based on combined extrusion are proposed, according to the authors, to evaluate friction characteristics in heavily loaded metal-forming operations. They differ in that parts of various shapes are formed: a double-sided cup [21, 22], a cup with an external axial ledge [23], a cup with an internal ledge [11], a

double-sided cup with a lower conical cavity [8, 20], or a cup with a conical ledge [20]. Calibration curves describing the relationship between the coefficient of friction and the changing dimensions of parts during the process are usually calculated based on an analysis of the flow of the material by FEM.

However, several researchers indicate that the loading and surface contact conditions in the extrusion of double-sided cups may not be comparable to the characteristic conditions of real cold deformation processes [22]. The accuracy of determining friction indicators in combined extrusion is hampered by stagnant zones, and to obtain stable results, it is necessary to optimize the geometry of the tool [23]. In addition, the results of experimental studies in these works are corrected using FEM models.

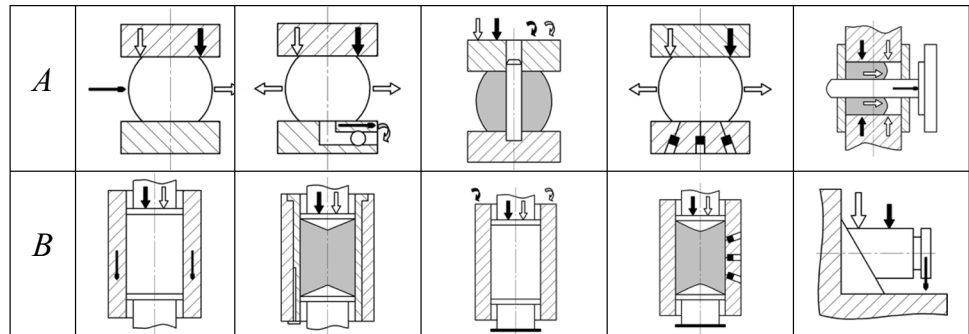
The method of extrusion of a T-shaped specimen [19, 24] is considered a universal one for studying and assessing contact friction, taking into account the characteristics of material flow on contact surfaces with different intensities of metal flow [25]. The relative volume of metal extruded into the V-shaped groove is used as a criterion for the simulation of friction conditions. A parametric study of this method carried out by FEM shows that the results of experiments are also influenced by the geometric parameters of the tools: a certain corner radius and angle of the groove in the die should be selected [23].

Group 4 includes methods for studying the distribution of specific friction forces on the contact surface of a tool using force-measuring pins (point load cells) [6, 7]. The advantage of these methods lies in the determination directly from the experiment of the friction stress field on the contact surface. However, measuring devices are characterized by significant complexity and labor-intensive setup [10]. The analysis of methods included in group 4 is described in detail in [6, 9]. The several devices from this group are discussed below in relation to upsetting processes.

Group 5 includes methods for measuring contact friction forces directly during the process of volumetric plastic deformation. It contains various methods (and devices) that can be classified according to the principle of operation, design and the deformation process realized. Initially, such methods of measuring friction forces were tried to be implemented on devices for upsetting [9, 10] and rolling [6, 26]. Let us consider the measuring devices of this group, dividing them into two subgroups: for upsetting (Fig. 1) and for volumetric die forming (extrusion and pressing).

Upsetting devices according to variant 1 (see Fig. 1) are based on the upsetting with the shear method. In open upsetting, the deformed specimen is simultaneously forcibly moved along the tool plane, recording the shear friction force [6, 26]. In closed upsetting (compression in a container), either the container or the specimen is forcibly displaced [6]. There are also known variants of devices that

Fig. 1 Schemes of devices for measuring friction forces during upsetting



provide for displacement or torsion of one of the punches (strikers) [7].

In upsetting devices containing split strikers (A2, B2), the forces or moment of friction forces arising during upsetting cause displacement of the movable part of the striker, which in turn acts on the recording load cell. Split strikers can be made rotary [10], sectional [6], or placed between deformable workpieces [9]. Devices with built-in movable sliders of various lengths are used [6] to measure friction forces on individual sections of the contact surface. A limitation in using the considered devices is the complexity of their adjustment to eliminate the influence of elastic deformations and thermal expansion of mating parts.

Devices for measuring friction forces during compression with torsion (variants A3, B3) are among the most common. By changing the torque, it is possible to find the dependence of the average specific friction forces vs the value of the normal pressure and the relative displacement of the strikers for various lubricants and temperature conditions [11]. The ability to change the sliding speed over a wide range can be attributed to the as-yet-unused advantages of the compression with torsion method [6].

The working tool for upsetting is often equipped with point load cells (variants A4, B4), which make it possible to measure normal forces simultaneously with the measurement of friction forces [9]. To perform such measurements in upsetting, bearing pin load cells are used [6], which reduce the negative influence of metal flow into the gaps of tools with split slides or point load cells.

Recording the displacement of the moving part of the tool for the open upsetting process is complicated by the influence of the stagnant zone of “sticking.” Reducing the negative influence of these features of the upsetting process with the recording of the displacement caused by friction can be obtained by using devices for upsetting with directed flow, made according to variants A5 and B5 [27].

The main disadvantage of methods and meters of this subgroup (upsetting) is the distortion of kinematic and force conditions on the contact surface, which is inevitable when using a cutting tool or artificial relative sliding of the specimen and the tool. Open upsetting, moreover, does not allow

achieving pressure values that significantly exceed the flow stress [10] and are characteristic of real-life conditions of the processes of volumetric die forming.

Measuring devices of the second subgroup of group 5 are intended for studying friction forces in the processes of volumetric die forming and, above all, extrusion. Measuring the resultant (integral) friction forces on part or entire contact surface, if it can be fulfilled, allows us to obtain more valuable information in comparison with other methods discussed above [1, 26]. However, several researchers point out the futility of using tools based on displacement measurements, because the measuring elements of the tool, which record the friction forces acting on its moving part, cannot record the friction forces at all in the presence of sticking and braking zones [7].

This limits abilities of the devices to realize traditional extrusion schemes. For example, in dies for backward extrusion, at a certain thickness of the bottom of the cup, the die can move upward due to frictional forces from the extruded metal [11]. The measurement of these forces is generally prevented by the inhibitory influence of the stagnant (unmovable) zone located under the area of intense deformation.

In forward extrusion, friction forces arise between the metal of the specimen and the container and are directed toward the outflow. Under the influence of these forces, the container also moves downwards, and if there were no obstacles to this, then the task of measuring friction forces would be solved. However, it is extremely difficult to eliminate the inhibitory effect of the die on the container because deformed metal and lubricant inevitably flow into the gap between them.

In the processes of drawing and forward extrusion of bushings on a mandrel, measuring friction forces is possible with a moderate discrepancy between the values of sliding velocities at the boundaries of the deformation zone, that is, only for small degrees of deformation [6, 10].

The foregoing confirms the relevance of considering and studying the possibilities of measuring contact friction forces directly in volumetric die forming processes. Expanding the possibilities for studying contact friction in extrusion

processes is important for the development of the theory and practice of metalworking under pressure in general. The accuracy of the results of theoretical analysis of force and deformation modes of forming processes, including that based on FEM, largely depends on the reliable determination and setting of boundary conditions on contact surfaces.

The purpose of the work is to develop and evaluate the capabilities of devices for directly measuring contact friction forces in volumetric die forming processes by extrusion.

3 Development of devices for measuring contact friction forces

The principle of action of measuring devices follows from the generalized definition of plastic friction (according to I.M. Pavlov) as the force interaction of two contacting bodies, one of which, the leading one (the initiator), promotes (or only strives to promote) the movement of the second, the lagging or driven body [26]. At the same time, two main cases should be distinguished. In the first case, when the initiator of friction is a deformable body, the lagging body—the part of the tool that acquires mobility due to the friction effect, acts on the recording element (load cell) with a certain force, which is recorded as the friction force. The accuracy of measuring friction forces depends on how successfully it was possible to identify the active contact surface and eliminate factors that prevent the movement of the tool under the influence of friction forces [28]. In the second case, the initiator of the observed friction is a specially moved part of the tool, and the force with which this movement is carried out is taken as the friction force. It is understood that the function of such active movements is purely measuring one, i.e., they should not cause any additional deformations of the specimen. Under this condition, characteristic of ordinary schemes for tribometric determination of friction constants, the case (3rd one) of moving the specimen itself with recording the moving force as a friction force is also possible if the deformation of the specimen is carried out by forces acting in a perpendicular plane.

The first case is more consistent with the actual conditions of deformation processes. In favor of variants that implement the second case, it can be pointed out that processes with active movement of the contacting parts of the tool are also used in practice [2, 11].

The use of extrusion schemes to study the contact friction factor is preferable and promising due to the possibility of providing the following advantages: wide variation of the main technological parameters, such as sliding speed, degree of deformation, hydrostatic pressure (backpressure) in the deformation zone, temperature, and deformation velocity; controllability and observability of energy-power and kinematic parameters; uniqueness of the metal flow direction

and the relative ease of finding zones of inhibited flow or stagnation (“sticking”); compactness; and turnover of the tool used [10].

The development of friction meters was preceded by structural analysis and search for a possible variety of extrusion devices, which are suitable for studying contact friction, and it was carried out in the following sequence. Initially, device designs were divided into types depending on the extrusion method implemented. Then, design variants for devices were considered depending on the kinematics of tool movement, the type of deformable part, and the friction initiators used [10].

In this work, we excluded design variants with cutting tools and with forced movement or rotation of workpieces or tools. Although, as is known, forced movement of the die (container) in one direction or another makes it possible to use the useful action of active or reactive friction forces. The force required for such movement in the ideal case of the absence of braking zones is directed at overcoming the frictional force between the deformed metal and the die walls and can be easily measured.

In transverse (radial and lateral) extrusion, the friction forces in the die-container are directional values and can be recorded at the metal sliding into a zone of intense deformation [2, 4].

A positive feature of the transverse radial extrusion process is the possibility of complete eliminating the forces expanding the transverse cavity due to the natural thinning of the extruded flange and subject to the absence of roundings of the transition edges of the die-container [10, 28]. This makes it fundamentally possible to accurately record the integral friction forces in the vertical cavity of the die [10, 29].

Schemes of newly developed devices for measuring friction forces (plastotribometers) in extrusion processes are shown in Fig. 2.

A device for measuring friction forces based on dies for radial extrusion of parts with a flange (Fig. 2, scheme a) contains a die-container 3 that acts on the load cell 5 and forms a radial cavity with the semi-die 4 for obtaining of the flange of the part [30]. When the punch 1 applies a load to the workpiece 6 covered with lubricant, deformation of workpiece and extrusion of metal into the radial cavity begin. The absence of rounding on the transition edge of the die-container 3 and the thinning of the formed flange contribute to the unhindered influence of the die-container 3 on the load cell 5 and the accurate recording of friction forces between the workpiece 6 and the surface of the vertical cavity of the die-container 3.

The operating principle of the device for extrusion of parts such as bushings is the same (Fig. 2, scheme b) [31]. Selecting the angle of inclination ($20^\circ \dots 30^\circ$) of the lower semi-die 4, which forms a radial circular cavity, makes it

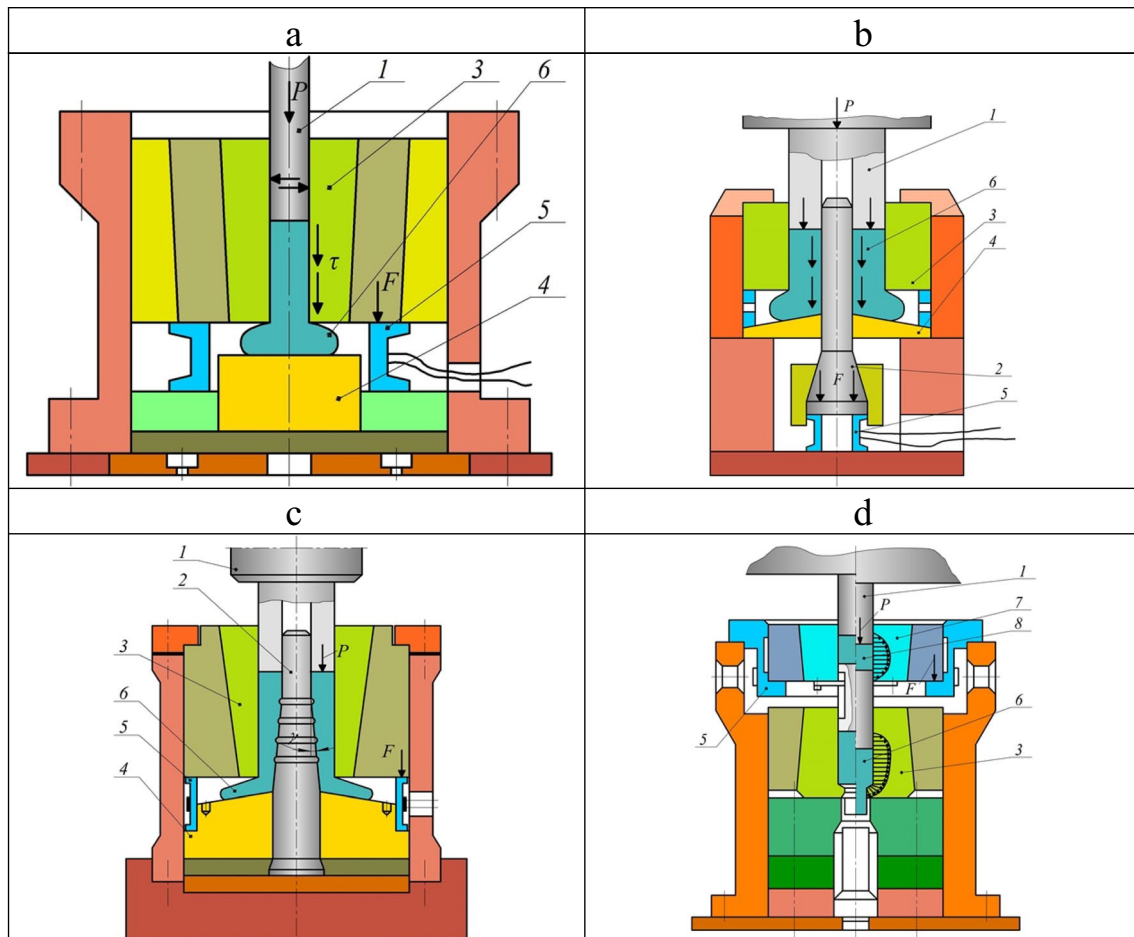


Fig. 2 Designs of contact friction force meters for the process of plastic deformation. (1) Punch. (2) Mandrel. (3) Die-container. (4) Semi-die. (5) Load cell. (6) Workpiece. (7) Container. (8) Specimen

possible to increase the accuracy of measuring the friction forces on the surface of the mandrel 2, leaning on the load cell 5.

Radial extrusion of hollow and rod-type parts with a flange is characterized by uniform conditions on the contact surface of the die-container and the mandrel [28]. In this case, an increase in the overall stroke of the punch can be achieved by combining radial and forward extrusion schemes [4].

Profiling a mandrel or die in a radial extrusion device is advisable to increase the degree of metal deformation in that part of the workpiece that initiates friction. If the friction force meter (load cell) is placed under the mandrel, then the surface of the die is profiled, and vice versa (see Fig. 2, scheme c) [32].

The difficulty of separating the forces (and pressures) of deformation and friction in the extrusion device under various schemes can be overcome by separating the measuring part of the device into a separate block with container 7 (see Fig. 2, scheme d) [33], located coaxially with the main

die-container 3. A reliable and accurate measurement of friction forces is achieved in the presence of an identical distribution of normal pressures on the contact surfaces of the die 3 and the measuring part (container) 7, equal sliding speeds, the state of the friction surfaces, and the rigidity of the tool. The limitation is due to the lack of renewal or expansion of the surface of the specimens 8 moving in a closed container.

Further work was aimed on searching and developing designs for lateral and longitudinal (backward and forward) extrusion schemes (Fig. 3). These extrusion methods with zones of intense plastic deformation and a high degree of surface expansion are characterized by significant uneven deformation and, accordingly, a difference in the velocity of metal sliding along the contact surface. As noted, zones of absence or slight movement (braking, stagnation) do not allow the transfer of friction force and distort the measurement results. Based on the assessment of the possibility of the appearance of stagnation and braking zones and determination of their sizes [10], devices have been developed for measuring friction forces, which provide for the separation

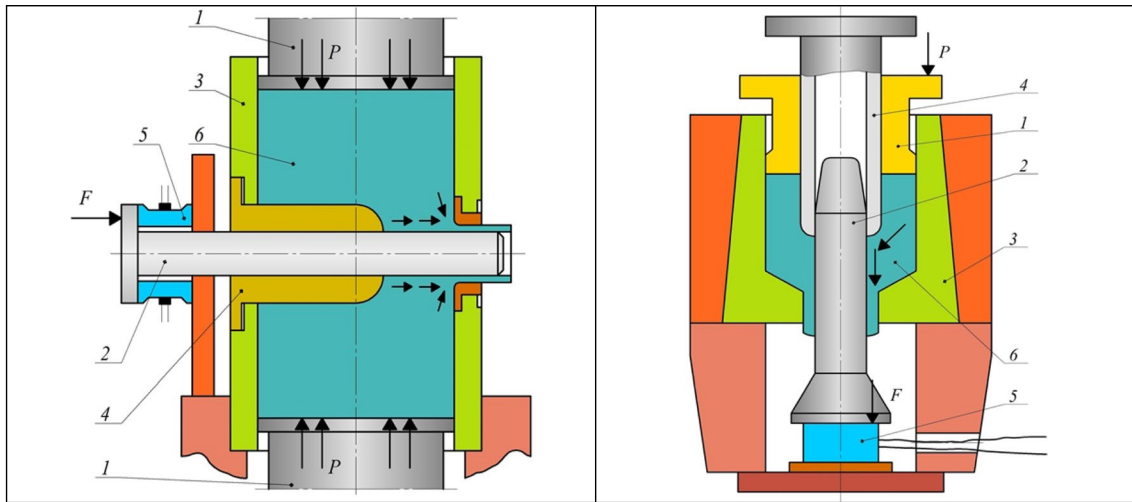


Fig. 3 Designs of devices with technological sleeve for measuring contact friction force in the process of plastic deformation. (1) Punch. (2) Mandrel. (3) Die. (4) Separating technological sleeve. (5) Load cell. (6) Workpiece

of the stagnation zone of the deformed workpiece 6 from the zone of intense deformation, using a technological sleeve 4, for lateral extrusion (Fig. 3, scheme a) [34] and longitudinal forward one (Fig. 3, scheme b) [35]. This allows the driven body—mandrel 2 to move freely under the influence of friction from the directionally extruded metal of the workpiece 6 and influence the load cell 5. The difference between the devices is that to simulate extrusion processes using them, it is necessary to prepare a special workpiece with profiled cavities.

The effectiveness of such separation of the stagnation zone for increasing the accuracy of measuring friction forces on the surface of the mandrel in the lateral extrusion device (see Fig. 3, scheme a) can be judged by the analogy of this scheme with the scheme of applying a metal shell to a cable, where the use of a sleeve is a prerequisite for the

stable course of the process. For detailed development of the design parameters of these devices, additional research of longitudinal and lateral extrusion schemes is required.

4 Measurement of contact friction forces and discussion of results

The purpose of the experimental studies was to test the developed devices and their capabilities for measuring friction forces under conditions of changing the characteristics of workpiece materials, temperature of deformation, and the composition of technological lubricants.

The universally adjustable equipment was used for the experimental study, installed on the test press MS-500 (Fig. 4). It can measure friction forces according to schemes

Fig. 4 Experimental stand based on the test press MS-500 (a). Technological equipment and specimens for deforming (b)



a–d (see Fig. 2). Materials of tubular and solid workpieces were aluminum alloys A93003, AA1135, AA6061, and steels 1010, 321. The diametric dimensions of the workpieces were 15.2; 21.2; and 28.2 mm. The tubular workpieces had diameters of 15.2/28.2 mm and 21.2/36.0 mm.

The technological lubricants used in the experiments were selected taking into account the recommendations of literary sources, as well as based on the need to study some lubricants developed by the St. Petersburg Institute of Applied Chemistry SIAC (graphitol V310, phosphatol 4 and 4G2, IFZh), Berdyansk Petrochemical Plant (ShS, Sokko, Sintefon, ZhKB), and DSEA 4 (oil + graphite + paste), which was developed in the chemical laboratory of the DSEA based on an oil suspension of graphite and molybdenum disulfide.

The study of contact friction forces carried out on devices—plastotribometers, shown in Fig. 2 (schemes a, b), made it possible to determine the effectiveness of some technological lubricants for cold extrusion. Assessment of the tribological

properties of lubricants based on changes in contact friction forces is justified because the quality of separation of friction surfaces is determined primarily by the conditions and force regime of friction.

The friction force curve responds noticeably to changing friction conditions. In Fig. 5, the record of force parameters (deformation and friction) is shown for the extrusion of a workpiece from aluminum alloy AA6061 with a diameter of $D_0 = 21.2$ mm with applied mineral lithium lubricant CIATIM 201.

In the same way, the surface quality of the extruded workpieces responds to changes in the technological lubricant. Based on the results of measuring friction forces in devices for transverse extrusion, the properties of several technological lubricants for cold and semi-hot deformation were assessed (Table 1).

Experimental data on the deformation and friction forces in radial extrusion of parts with a flange on a device with a ring load cell 5 (see Fig. 2, scheme a) are given in Table 1. Parameters of the workpiece and part: diameter D_0 , flange thickness h , and punch stroke S are given there. The height of the initial workpiece H was 50 ± 3 mm.

Based on the results of measuring friction forces, curves of changes of specific friction forces f during radial extrusion of samples with flanges were determined, which are presented in Figs. 6, 7, 8, and 9.

For the integral characteristic of contact friction conditions, the value of the average specific friction force (stress) was used:

$$f = F/S_k, \quad (1)$$

where F —is the experimental value of the force of contact plastic friction according to the load cells readings;

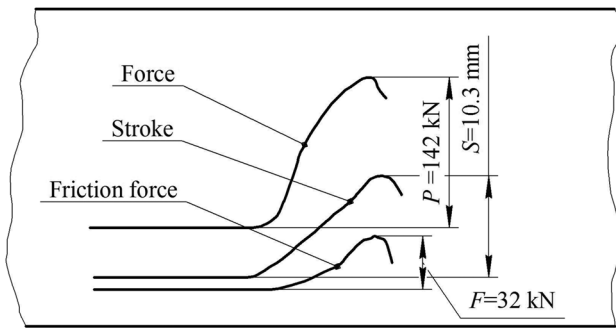


Fig. 5 Typical oscillogram of the deformation process

Table 1 Results of measuring forces of cold radial extrusion and contact friction forces

No.	S/h , mm/mm	P , kN	Lubricant	F , kN	f , MPa	$\mu = f/\sigma_s$
Aluminum alloy AA6061, $D_0 = 21.2$ mm						
1	13.9/9.0	100	Thiokol	1.0	0.5	0.002
2	9.0/4.5	130	Wax (in oil)	2.8	1.6	0.008
3	14.8/9.0	112	Animal fat	3.5	2.6	0.010
4	17.0/9.1	140	VNIINP 232	6.0	3.8	0.020
5	7.5/4.5	130	Mineral oil	12.0	6.4	0.030
6	14.2/9.1	140	Paraffin	27.2	11.4	0.050
7	9.0/4.5	200	IFZh	37.5	21.4	0.090
8	4.0/4.5	270	Talc	210.0	101	0.466
Steel 1010, $D_0 = 15.2$ mm						
9	19.4/5.1	282	Phosphating with saponification	64.6	38.2	0.045
10	17.5/5.1	280	VNIINP 232	75.2	42.1	0.050
11	20.8/5.1	320	Teflon (PTFE)	96.5	59.2	0.070
12	22.0/5.1	352	Graphite with oil	96.0	68.1	0.080
13	18.0/5.1	309	Mineral oil	134.0	76.0	0.090

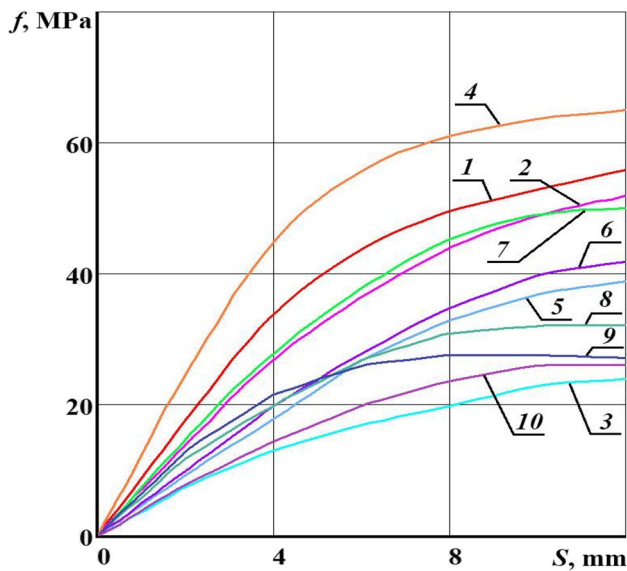


Fig. 6 Diagrams of specific friction force changes for cold extrusion of workpieces (steel 1010, $D_0 = 21.2$ mm) with lubricants. (1) Oil + stearate. (2) Oil + graphite. (3) Phosphating + soap. (4) Mineral oil. (5) DSEA 4. (6) VNIINP 232. (7) ShS4. (8) Sokko. (9) Sintephone. (10) ZhKB

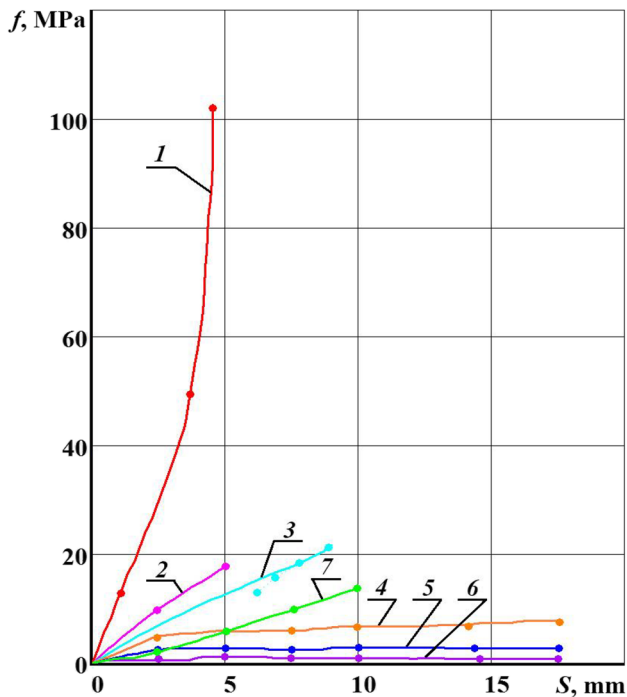


Fig. 7 Curves of specific friction force changes for radial extrusion of workpieces (aluminum alloy AA6061, $D_0 = 28.2$ mm) with used lubricants. (1) Talc. (2) phosphatol 4G2. (3) IFZh. (4) castor oil. (5) VNIINP 232. (6) lanolin. (7) CIATIM 201

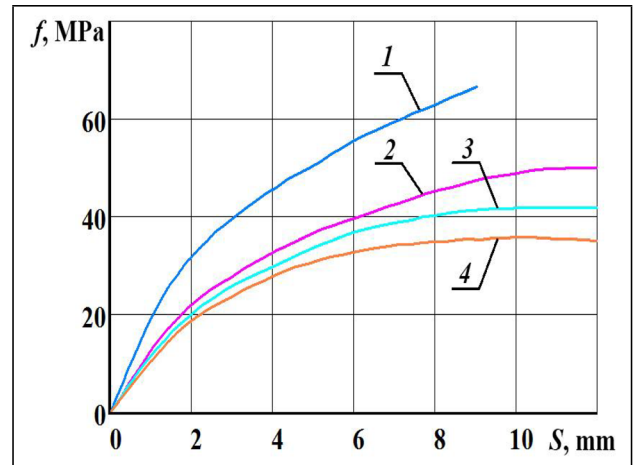


Fig. 8 Specific friction forces for semi-hot extrusion

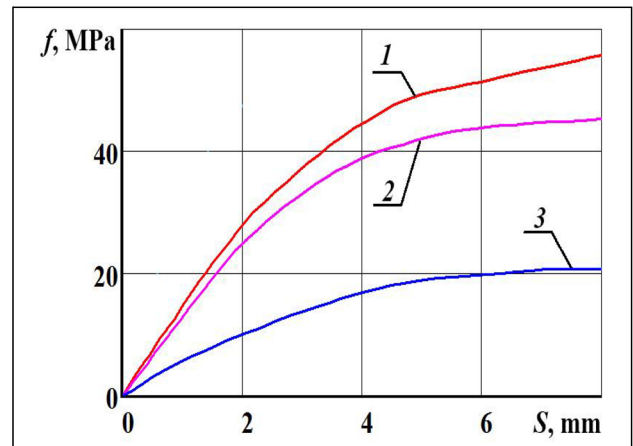


Fig. 9 Specific friction forces for extrusion of workpieces from titanium alloy Ti Grade 23/R56401

S_k —the contact area of the deformed workpiece with the moving part of the tool.

Various variants for identifying contact friction stresses are used in simulation plastic deformation processes [1, 6].

The value of the specific friction force (stress) is divided by the average flow stress of the metal in the deformation zone according Siebel's friction law:

$$\mu = f / \sigma_s, \quad (2)$$

where μ —the Siebel's friction coefficient; σ_s —the flow stress of the workpiece material.

To characterize the friction conditions, we also used the ratio of the friction force F (or friction stress f) to the extrusion force on the punch P (pressure p):

Table 2 Coefficients G and B included in formula (8)

Material	G	B
Armco steel	4.65	311.6
Steel 1010	5.33	442
Copper C11000	4.65	186
Aluminum alloy A93003	10	380
Aluminum alloy AA6061	10	430
Aluminum alloy AA1135	8.33	200

$$\Psi = F/P \text{ or } \psi = f/p, \quad (3)$$

where p —is the specific force (pressure) of extrusion.

In Fig. 8, the curves were plotted using the results of measuring friction forces during semi-hot (700...800 °C) extrusion of workpieces with a diameter of $D_0 = 28.2$ mm from steel AISI 1010 with lubricants: 1—oil + chalk + graphite, 2—oil + graphite, 3—oil + bitumen + graphite, 4—DSEA 4.

The curves of changing specific friction forces during extrusion (750...800 °C) of workpieces with a diameter of $D_0 = 28.2$ mm from titanium alloy Ti Grade 23/R56401 with lubricants: 1—oil + graphite, 2—oil + bitumen + graphite, 3—DSEA are shown in Fig. 9.

As follows from the results obtained, the next technological lubricants are the most effective for cold extrusion processes:

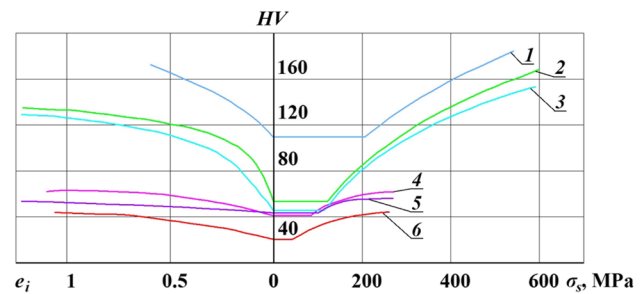
- for aluminum alloys—thiokol, lanolin, and animal (mutton) fat;
- for low-carbon steels—phosphating followed by saponification, ZhKB, Sintefon, and phosphatol 4G2.

Graphitol V310 gives results close to Sokko and Sintephone lubricants.

The use of lubricant based on MoS_2 (VNIINP-232 paste), as well as DSEA 4 lubricant, gives good results for processes with a noticeable renewal of the surfaces of the deformed workpiece because it avoids metal sticking to the surface of the tool. For semi-hot extrusion of steel and titanium workpieces, DSEA 4 turned out to be the best.

For a visual representation of the effectiveness of technological lubricants, the friction coefficients calculated using formula (2) according to Siebel's law for the final stage of the process, are given in Table 1. Note that the values of friction coefficients μ , obtained for most lubricants, are lower than the usually recommended values for most lubricants and do not exceed 0.1. This made it possible to refine the process models for predicting power modes and forming deformed parts [4, 28].

The value of the specific friction force is an important factor of friction along with the friction coefficient. It is


Fig. 10 Calibration diagrams “Hardness HV —flow stress σ_s ”. (1) Armco steel. (2) Copper C14200. (3) Copper C11000. (4) Aluminum alloy A93003. (5) Aluminum alloy AA6061. (6) Aluminum alloy AA1135

consistently dependent on the hardness of the metal in the near-boundary layer and can be used as a reliable indicator of the tribological properties of technological lubricants and the conditions of contact friction for plastic deformation. A comparison of the experimentally obtained data on the specific friction forces f and the normalized radial extrusion pressure $\bar{p}$ showed that the relationship between them is exponential, as it was indicated in the works of a number of researchers [9, 36].

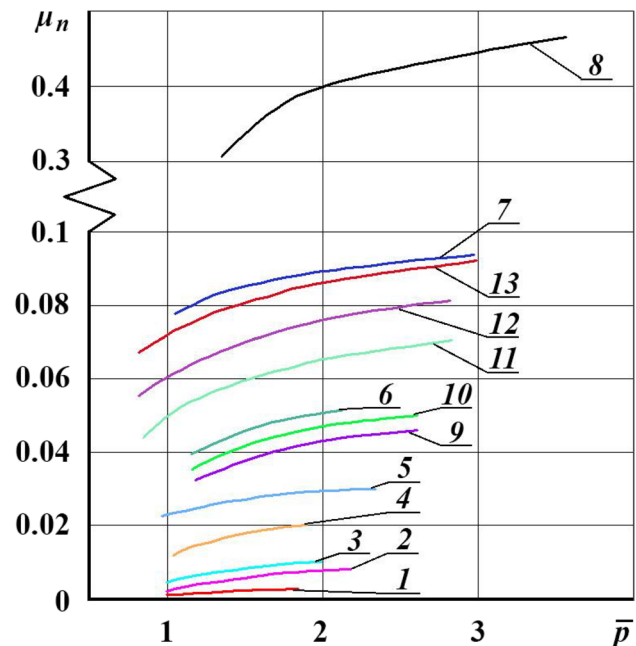

Fig. 11 Dependence of the friction index μ_n vs the normalized pressure $\bar{p}$ for radial extrusion of some materials and used lubricants: steel 1010 (curves 9–13); aluminum alloy AA6061 (the rest ones). (1) Thiokol. (2) Wax. (3) Fat. (4), (10) VNIINP-232. (5, 13) Mineral oil. (9) Phosphating. (6) Paraffin. (11) Teflon (PTFE). (12) Graphite with oil. (7) IFZh. (8) Talc

Table 3 Values of coefficient K_c

Curve no.	1	2	3	4	5	6
K_c	0.004	0.013	0.016	0.023	0.030	0.057
Curve no.	7	9 (8)	10	11	12	13
K_c	0.096	0.048	0.053	0.074	0.085	0.095

Exponential dependence for specific friction forces proposed by Levanov A.N. has the form [9]:

$$f = K_S \cdot [1 - e^{-n \cdot \sigma_n / \sigma_{sk}}] \cdot (\sigma_{sk} / \sqrt{3}), \quad (4)$$

where K_S —is the surface constant, $0 \leq K_S \leq 1$;

σ_n —the geometric sum of normal p_n and tangential f stresses;

n —approximating coefficient, $n = 1.25$;

σ_{sk} —the flow stress of the near-contact layer.

The difficulty of using exponential dependencies of type (4) is that they include in various forms the normal pressure at the contact and the flow stress in the near-boundary layer of material, for the determination of which there are no recommendations [9, 36].

Simplification of formula (4), using the assumption that the relative normal pressure at the contact is equal to the normalized extrusion pressure $\bar{p} = p / \sigma_s$, i.e., $\sigma_n / \sigma_{sk} = \bar{p}$, and the flow stress σ_{sk} of the near-boundary metal layer can be expressed approximately in terms of the metal hardness indicator of this layer HV [37], allowed us to recommend the formula:

$$f = K_c \cdot \left[1 - \frac{1}{e^{n \cdot \bar{p}}} \right] \cdot T_h, \quad (5)$$

where K_c —a coefficient depending on the conditions of contact friction, $0 \leq K_c \leq 0.5$;

n —approximating coefficient, $n = 1.25$;

$T_h = \sigma_{sk}$ —a function of the hardness of the near-boundary layer.

T_h can be specified by a dependency of the form:

$$T_h = G(HV) - B. \quad (6)$$

The coefficients G and B (Table 2), included in expression (6), are obtained by approximating calibration diagrams of hardness “ $\sigma_s - HV$ ” of materials, constructed using the results of frictionless upsetting of cylindrical specimens. Some of these diagrams are shown in Fig. 10.

It should be noted that the measured hardness values of the contact surface are slightly higher than ones at a distance of 3–5 mm from the near-boundary layer deep into the body of the workpiece. The difference was 5–8 units for aluminum alloy AA6061 and 20–40 units for steel 1010, and the surface hardness HV reached 62–63 and 180–200 units, respectively.

Using Eq. (5), we introduced the friction indicator (relative friction stress) μ_n , which can be used to set the conditions of contact friction depending on the level of normalized pressure:

$$\mu_n = f / T_h = K_c \cdot \left[1 - \frac{1}{e^{n \cdot \bar{p}}} \right]. \quad (7)$$

The dependences of the friction indicator μ_n vs the normalized radial extrusion pressure $\bar{p}$, obtained experimentally for various friction conditions (Fig. 11), are also exponential. In this case, the material of the workpiece and the type of lubricant used have the most significant influence. By processing the experimental data (see Fig. 11), the values of the coefficient K_c (Table 3) in formula (5) were obtained, considering them in the form of a limit for the growth of contact friction at values of normalized pressure $\bar{p} \approx 4$.

Processing of the obtained results showed that the values of the friction indicator μ_n , as expected, diverge from the values of Siebel’s friction coefficient μ (see Table 1). The value of μ_n exceeds μ by approximately 1.12...1.2 times in the extrusion of workpieces from alloy AA6061 and 1.4...1.6 times in the extrusion of workpieces from steel 1010. In general, they are in good agreement with each other and respond equally to changes in contact friction conditions. Further justification of dependence (7) is associated with the need for a more in-depth experimental analysis of extrusion processes using the developed plastotribometers and with varying technological factors such as deformation rate and deformation temperature of various materials.

The results of measuring the friction forces made it possible to find that the share of friction forces in the total value of the deformation force ranges from 1 to 23% in the extrusion of aluminum alloys and from 18 to 43% in the deformation of steel 1010. For deformation with the worst lubricants, the share of friction forces can reach up to 2/3 of the total deformation force. The results obtained made it possible to clarify the idea of the level of contact friction forces and to reasonably accept the values of friction indicators (coefficients) in simulations of extrusion processes [4].

5 Conclusions

Analysis of methods and means for assessing contact friction conditions confirms the advantage of methods for directly measuring friction forces in plastic deformation

processes compared to methods for indirectly determining friction constants using deformation, kinematic, and force parameters.

The designs have been developed for measuring friction forces in the processes of extrusion of parts from solid and hollow workpieces at various deformation temperatures. It has been determined that the use of radial extrusion schemes and devices for measuring contact friction forces is preferable and promising due to the possibility of ensuring force interaction between two contacting bodies, one of which is leading (the initiator), contributing to the unhindered movement of the second one—driven body.

The possibility of assessing the effectiveness of technological lubricants based on the results of experimental values of specific friction forces has been discovered. At the same time, the values of the friction coefficients based on the flow stress (according to Siebel's law) were clarified.

A refined exponential formula is proposed for determining friction stress depending on the normalized deformation pressure, in which the flow stress of the near-contact metal layer is expressed in terms of hardness indicators.

Devices for measuring friction forces directly in extrusion processes serve as the basis for the development of plastotribometers, which make it possible to conduct comprehensive studies to assess the influence of temperature-speed and energy-force modes of deformation for various materials on the indicators of contact plastic friction.

Author contributions By Igramotdin S. Aliiev: measurement of contact friction forces and discussion of results.

By Vladymyr N. Levchenko: development of devices for measuring contact friction forces.

By Oleg E. Markov: measurement of contact friction forces and discussion of results.

By Aleksander V. Kalujnyi: development of devices for measuring contact friction forces.

By Leila I. Aliieva: introduction; methods for evaluation of friction conditions in volumetric metal forming.

By Roman I. Sivak: development of devices for measuring contact friction forces.

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Code availability Not applicable.

Declarations

Ethics approval This manuscript was submitted to only one journal. The submitted work is original and does not have been published elsewhere in any form or language (partially or in full). Results have been presented, honestly, and without fabrication, falsification, or inappropriate data manipulation (including image-based manipulation). The authors adhered to rules for acquiring, selecting, and processing data. Data, text, and theories were the author's own. Proper acknowledgements of other works were given and summarized.

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