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WEAR PROCESSES IN PRECISE PAIRS OF HYDRAULIC CONTROL DEVICES

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Abstract

One of the most important tasks in a complex of activities aimed at increasing the use quality of a hydraulic drive are studies concerning the impact of operating conditions of hydraulic precise pairs on their durability. With supercritical values of the slide velocity, there is a stepwise and rapid quantitative characteristics of the wear process on the surface of a hydraulic precise pair's elements. The phenomenon of wear by oxidation and the occurrence of adhesive seizing (tacking), created in the course of the process of mutual impact of surfaces of hydraulic precise pairs in control devices, under load resulting from a hydraulic drive's pressure pulsation requires thorough consideration. The paper discusses operating conditions of slider pairs of hydraulic control devices associated with the kinetics of their movement and their load conditions. They were supported by results of empirical studies. General characteristics and mechanism of the wear by oxidation in a slider control pair was presented. The impact of loss of stability of a control spring in a slider control pair and the relative displacement of pair's elements during the operating process, on the character and intensity of the adhesive seizing event were discussed. The conditions of occurrence of adhesive seizing in hydraulic slider pairs, under load resulting from pressure pulsation in a hydraulic drive were discussed.

Keywords: *aviation, hydraulic drive, hydraulic precise pair, wear by oxidation, adhesive seizing, tacking*

1. Introduction

Though knowledge about wear mechanisms has significantly developed, we still lack a general image of the impact process under specific conditions of cooperation between elements of a precise pair [1, 2, 5-8, 13, 18, 19]. Lack of complete knowledge in the scope of the impact of operating conditions of hydraulic precise pairs on the character of the destructive processes arising in them, results in not taking these conditions into account at early stages of design and manufacturing. Therefore, there is a need to identify and describe the wear processes in hydraulic precise pairs, especially with their load resulting from pressure pulsation in a hydraulic drive or uneven distribution of the operating fluid's pressure in the ring aperture (structural clearance), created by the slider and the bushing. Identification of destructive factors occurring in hydraulic precise pairs and their description, will allow designing hydraulic drives in such a way, so the wear of their precise pairs is minimal.

The aim of this article is to describe the operating conditions of hydraulic slider pairs of control devices and the impact of those conditions on their wear process.

On the basis of data available in the scientific-technical literature, it can be said that the dominating wear process in hydraulic precise pairs should be wear by oxidation [1, 3-5, 11, 13, 14, 18]. The fact that the wear due to oxidation process is dominating during operation of a hydraulic precise pair, guarantees low wear intensity of cooperating pair surfaces [1, 4, 5, 13, 14]. Wear due to oxidation is conditioned mainly on maintaining, during operation, the load (pressure and sliding velocity) in a hydraulic precise pair, below the critical value. With supercritical values of the slide velocity, there is a stepwise and rapid quantitative change of the friction coefficient between the surfaces of hydraulic pair's elements [12, 18, 19]. After reaching the critical slide velocity, the adhesive seizing process is initiated and tacking processes of cooperating surfaces of a hydraulic pair start to dominate on friction surfaces [10, 12, 18, 19].

When studying the damageability of precise pairs, usually all the attention was paid to the development of fretting-corrosion, i.e., to abrasive-oxidizing processes [3, 4, 10, 11, 14]. There is a view that in the initial stage of the fretting-corrosion process, there is tacking in micro-section of the surface contact area. Tacking is stopped as the correlated surfaces' wear products accumulate in the contact area [1, 13, 14]. It stems from the fact that during vibration friction and an oxidized contact zone, damages are created in the form of pitting, filled with damage products, containing mainly of powdered oxides of metals in contact [4, 14, 16]. To develop such a process, relative displacements of touching sections of correlated surfaces, measuring part of a micrometre. The mentioned papers do not discuss the influence of the ratio of contact surface dimensions and the displacement size of a hydraulic pair's elements, as well as the periodicity of contact breach, on the creation and development of tacking during vibratory slide. The migration of wear products from the area of cooperation of a precise pair's elements is also not taken into account. That is why the results of such studies cannot be used to explain causes and regularities of adhesive seizing (tacking) occurrence in hydraulic precise pairs, taking over contact-vibration loads.

2. Operating conditions of slider pairs of hydraulic control devices

The most common in hydraulic drives are control slider pairs, which consist of perceiving and control elements, automatically limiting or changing, acc. to the set pressure, its drop (pressure difference) in connected volumes (surfaces) or the output of the operating fluid. Hydraulic slide pairs, due to the nature of their movement, operate in conditions of contact load and slide, taking over only axial loads.

Hydraulic control pairs, acc. to the kinetics criterion of their movement and load conditions are characterised by the following features:

- the slider performs a constant reciprocating movement in relation to the cylinder, due to changes of the operating fluid's pressure and the return movement of the spring and also transfer the double-sided changeable axial pressure from the operating fluid's and the spring's pressure,
- relative slide velocity of the slider in relation to the bushing and its acceleration depend on the output of the operating fluid reaching the pair, the stiffness of the spring and the slider's mass,
- the slider is tilted under the impact of ever-present eccentricity of the resultants of the operating fluid's forces and spring applied to the slider
- the slider vibrates in the axial direction, as a result of pulsation from the operating fluid's pressure.

One-sided radial pressing of the slider to the bushing might be caused by the radial force created as a result of loss of stability of the slider hydraulic pair's spring and/or radial force created as a result of uneven distribution of the operating fluid's pressure in a ring aperture (structural clearance).

As a result of the tilting of the slider in the bushing, the operating fluid's force and the axial component of the spring force create a pair. The size of the torque depends on the size of the clearance in the slider pair and the clearance between the slider head and the spring. Diagram of forces impacting a slider of a typical control device, during loss of the spring's stability is presented in Fig. 1

The magnitudes of the forces pressing the slider to the bushing have the form of:

$$P_1 = \frac{P_c}{l}\left[\delta_{st} + \frac{\delta_{ss}}{2} + \frac{L-l}{2L_{sp}}(\delta_{st} + \delta_{ss} + \delta_{sk})\right] \quad \text{or} \quad P_1 = P_c \cdot tg\alpha \cdot \frac{L}{l}, \tag{1}$$

$$P_2 = \frac{P_c}{l}\left[\delta_{st} + \frac{\delta_{ss}}{2} + \frac{L-l}{2L_{sp}}(\delta_{st} + \delta_{ss} + \delta_{sk})\right], \tag{2}$$

where:
P_c– force coming from the operating fluid's pressure,
P_1 and P_2 – pressing force of the slider to the bushing,
$\alpha = arctg\frac{\delta_{st}+\delta_{ss}+\delta_{sk}}{2L_{sp}}$ – angle between the spring force line of action and its cap,
δ_{sk} – clearance circle between the spring and its cap,
δ_{st} – clearance circle between the slider and the bushing,
δ_{ss} – clearance circle between the slider head and the spring,
l – distance between the middles of the slider and bushing planes of contact,
L – distance from the slider head to the middle of the slider and bushing plane of contact,
L_{sp} – length of spring.

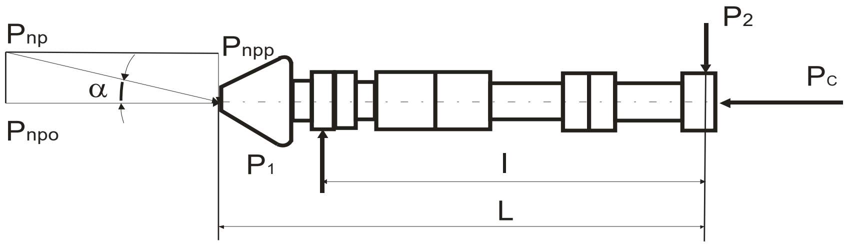

Fig. 1. Diagram of forces impacting a slider of a control device's hydraulic pair, during loss of the spring's stability

One-sided radial pressing of the slider to the bushing might also be caused by the radial force created as a result of uneven distribution of the operating fluid's pressure in a ring aperture (structural clearance). In the case of ideal parallelism of the cylindrical surface of the slider and the bushing, the pressure in the clearance decreases linearly and the radial forces balance in any symmetric configuration of the piston and the bushing in relation to each other. In the case a shape lapse of cylindrical surfaces of the slider and the bushing, the equilibrium of radial forces is breached, resulting with the creation of forces and moments, which move the slider towards one or the other side of the bushing surface. Fig. 3 presents the diagrams of shape lapses of cylindrical surfaces of sliders and bushings of a hydraulic pair with applied graphs of radial forces. In Fig. 3, the radial forces are contained between the curves of pressures a and b, respectively, for the upper and lower aperture. The direction of the radial forces is marked with arrows. The greater the surface contained between two curves of pressures a and b, the bigger the force pressing the slider to the bushing (Fig. 3). In the case of a conical clearance widening in the direction of fluid leaks (Fig. 3a), the slider in the bushing is unstable and in the case of concentricity, there will be an unbalanced radial force, which shall aim for moving the piston towards the smaller clearance, until it is in contact with the bushing. The bigger the radius of the eccentric and the curvature of the slider axis, the bigger the radial force causing the deadlock. With higher radial clearances between the slider and the bushing, there can be higher curvatures and eccentricities, thus, the clamping force will increase.

3. Studies on the movement character of elements of control slider pairs

In the operation process, the elements of hydraulic slider pairs of control devices, constantly or periodically, as a result of the changing pressure of the operating fluid, perform relative reciprocating movements at different frequency and amplitude. At the same time, the movement frequency and amplitude depend on the character of the pressure change (pulsation) of the operating fluid and change, depending on the operating range of the control unit. The slider movement amplitude depends on the size of the operating fluid's pressure change and the spring stiffness. The pulsation sources in a hydraulic drive are the hydraulic pump efficiency pulsation and transition states of hydraulic systems [2, 5, 7, 8, 15, 17].

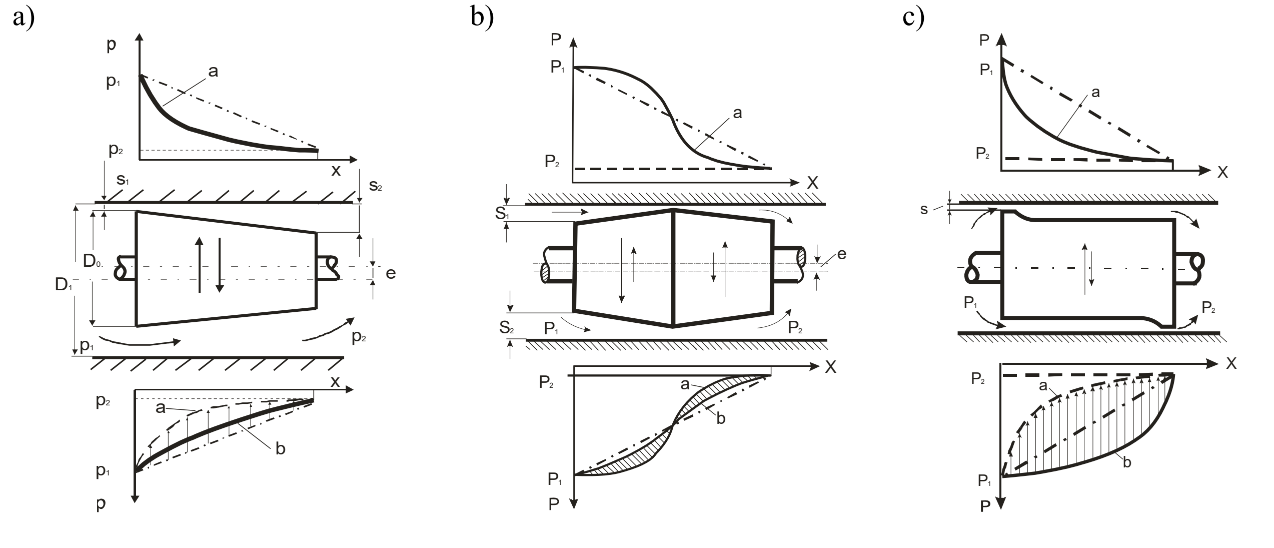

Fig. 3. Diagrams of the impact of unbalanced radial forces on the slider of a hydraulic precise pair

A device enabling imitation of vibration of these pairs was constructed to test the movement character of control slider pairs' elements under the impact of operating fluid's pressure pulsation. The diagram of the device is presented in Fig. 4.

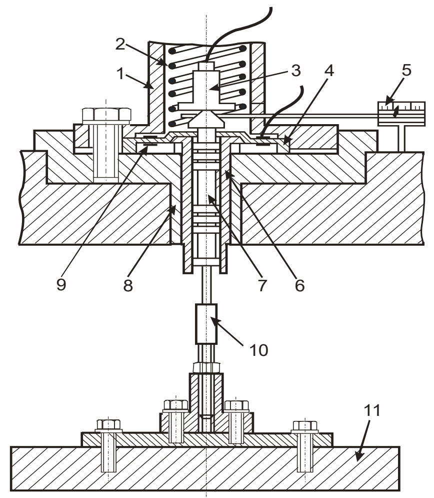

Fig. 4. Diagram of a stand imitating the vibratory displacement character of the slider hydraulic pair's elements under the influence of the operating fluid's pressure pulsation: 1) valve body, 2) spring, 3) vibration sensor, 4) elastic ring, 5) force sensor (dynamometer), 6) hydraulic pair bushing, 7) hydraulic pair slider, 8) device body, 9) tensometric sensor, 10) stem of the vibration plate with a vibration sensor, 11) plate of the vibration device

Elements of control slider pair are fastened to a device, which allows carrying out slider movements due to vibrations of the vibration plate. A stationary element of a control slider pair, which is the bushing (6, Fig. 4), is placed freely in a central opening of the device's body (8). Elastic ring (4) keeps the bushing in the axial direction. At the same time, it is the perceiving element when measuring the friction force in a hydraulic pair. With its central part, the ring (4) is put on the bushing head (6) and pressed along the perimeter by the valve body flange (1) to the body of the device (8). The necks connecting the central and external part of the ring (4) have stuck tensometric sensors (9), which react to deformations of the necks, when the bushing tends to move upwards. Because a bushing can move in the axial direction only under the action of the slider's friction force, the sensors register the friction in the hydraulic pair. Slider (7) of a hydraulic pair is inserted freely into the bushing (6). Longitudinal vibratory displacements are transferred to the slider (7) through a stem of the vibration plate (10), fastened on the plate (11) of the vibration stand. An operating spring of the control elements acts on the slider from the top, through a locking plate, with a spherical contact surface. Depending on the needs (requirements), the spring compression degree (e.g. the effect of loss of stability affecting the slider) may be changed. Hydraulic oil is inserted into the control hydraulic pair during the tests. Relative movement of the slider (7) on a backing pad is registered by a piezoelectric sensor (3). The stem of the vibration plate (10) has a built-in piezoelectric vibration sensor. Piezoelectric sensors (3) and (10) and the tensometric sensor (9) are connected with wires to a recording device.

Laboratory tests of a slider pair of the constant pressure valve and the pressure increase limiter were performed on the above-mentioned stand. Experimental testing showed that the size of the slider's displacement amplitude changes depending on the frequency (Fig. 5). In the constant pressure valve, for frequencies below 50 Hz, the displacement amplitude changes accordingly, from 0.3 mm to 0.04 mm. For frequencies from 100 Hz to 400 Hz, the displacement amplitude is set at a level of 0.005 mm. In case of the pressure increase limiter, for the frequencies from 30 Hz to 250 Hz, the displacement amplitude changes accordingly, from 0.3 mm to 0.5 mm. For frequencies above 250 Hz, the displacement amplitude is set at a level of about 0.05 mm. Curves in Fig. 5 may be the envelope for the vibration parameter range, which correspond the work conditions of the control slider pairs.

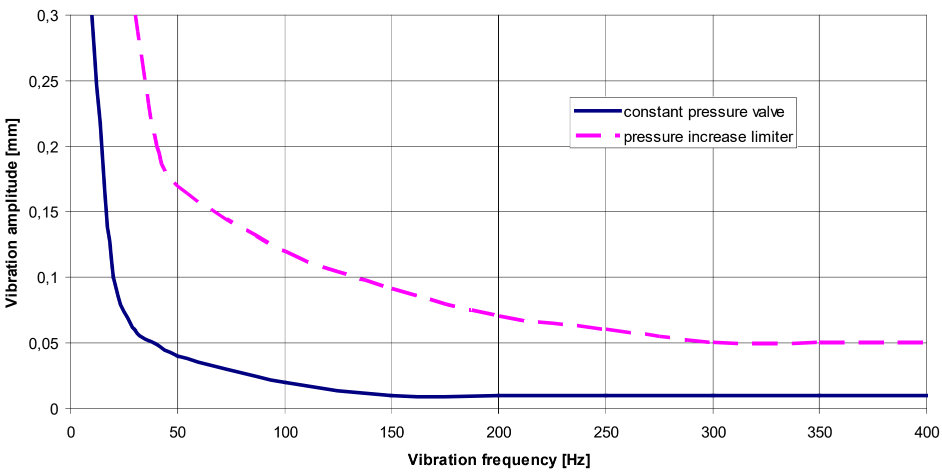

Fig. 5. Range of vibration parameters, with corresponding operating conditions of control slider pairs

4. Wear by oxidation (normal) in slider control pairs

The fact that the wear due to oxidation process is dominating during operation of a hydraulic precise pair, defined as normal wear, guarantees low wear intensity of cooperating pair surfaces [1, 3, 4, 9]. The wear by oxidation takes place when the formation speed of oxide layers (for steel FeO, Fe_2O_3, Fe_3O_4) is greater than the speed of their abrasion from friction surfaces. The top steel layer is characterized by different oxygen saturation. Upper zone with a thickness of 10-45 µm contains Fe_2O_3 [1, 9]. The zone located deeper, with a thickness of 50-120 µm is a magnetic Fe_3O_4 [1, 9]. The zone bordering the core, with a thickness of 70-150 µm contains FeO [1, 9]. Hardness and abrasion strength of oxide layer is mostly few times the hardness and abrasion strength of the core [1, 9].

The paper [18] presents the results of laboratory tests concerning the wear character of a precise pair's elements, one made of chrome steel (HRC = 62) and the other of carbon steel (HRC = 42), mutually sliding on each other. The tests were conducted for 50 hours, at the slide velocity of the precise pair's elements of 1 m/s and different unit pressures. The test results, in the form of relations between the composition of the wear product of the precise steel and unit pressures are presented in Fig. 6. It needs to be added that the biggest wear intensity of precise pair's elements occurred with unit pressures from the range of 0.2 MPa to 0.8 MPa. At the peak point, with the pressure of 0.7 MPa, the wear intensity was around $0.85 \cdot 10^6$ g/cm^2. With pressures above 0.8 MPa, there was a decrease in the wear intensity of the precise pair's elements, to the value of around $0.3 \cdot 10^6$ g/cm^2. The graph in Fig. 6 indicates that for unit pressures below 0.8 MPa, the main wear products are ferric oxide FeO and iron Fe, while above 0.8 MPa, the iron oxide Fe_2O_3. Here, we can draw a conclusion that decreasing wear intensity of precise pair's elements was caused by the formation of the iron oxide Fe_2O_3, which protects metal surfaces against intensive abrasion. After the slider of a hydraulic pair reaches the critical slide velocity, the adhesive seizing process is initiated and tacking processes of metal surfaces of the hydraulic pair start to dominate on friction surfaces.

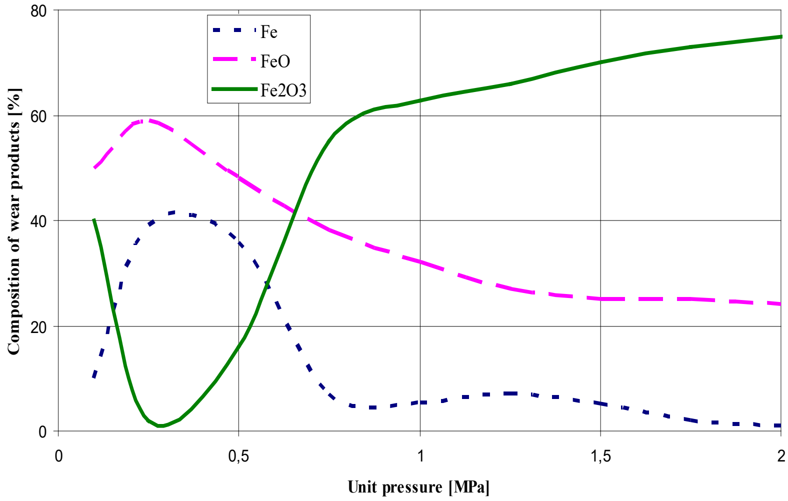

Fig. 6. Composition of wear products of chrome steel sliding on carbon steel

5. The process of occurrence of adhesive seizing in hydraulic slider pairs, under load resulting from vibrations of the slider in the axial direction

By adhesive seizing in hydraulic slider pairs, we will understand a self-fading tacking process of pair surfaces, operating in conditions of a slide caused by pressure pulsation and slider vibrations in the axial direction. The distinguishing properties of adhesive seizing occurrence in hydraulic slider pairs are small sizes of relative displacements of correlated surfaces of the slider pair, the size of the slide velocity and the formation speed of metal oxide layers on cooperating surfaces of the hydraulic pair, as well as the speed of their abrasion.

In order to determine the most favourable vibration ranges, in terms of adhesive seizing occurring on cooperating surfaces of a slider pair, experiments were conducted on a vibration stand, of which the diagram is presented in Fig. 3. A slider pair of the pressure controller was tested. Average test length was 15 min. The controller slider was pressed axially with a force of the pressing spring of 50 N to 100 N, and laterally, with a force of 25 N to 50 N. The results of experiments of the pressure controller's slider pair in an ASF-41 oil environment are presented in table 1. It was found that the most favourable, in terms of tacking occurring, is the vibration scope in the amplitude range of 0.005 – 0.1 mm. At amplitudes below 0.005 mm, adhesive seizing was poorly exposed. During analysis of the model of the process-causing adhesive seizing (tacking) in a slider hydraulic pair under its contact-vibration load, the following needs to be taken into account:

- abrasion speed of metal oxides (decrease of the surface occupied by them over a unit of time)

and formation of metal oxides (decrease of the surface occupied by them over a unit of time)
- actual contact surfaces of the hydraulic pair's elements, practically unchanged until adhesive seizing (tacking) occurs,
- actual contact surfaces coated with metal oxides and without metal oxides,
- load, defined with values of normal load (pressure) in a point of contact of correlated pair surfaces and velocities of relative slide of correlated slide surfaces,
- time between surfaces without metal oxides appears and metal oxide layers are formed on these surfaces.

Tab. 1. The results of experiments of the pressure controller's slider pair in an ASF-41 oil environment

Vibration range [mm]	Wear character
< 0.005	Tack welding not exposed at a load up to 100 N. At a load in the range of 140-150 N poorly exposed tacking marks (small dimensions).
0.01	Tacking marks at a load of approx. 30 N.
0.05	Tacking marks at a load from the range 40-50 N.
> 0.1	Marks characteristic for intensive oxidation wear of metal surfaces.

When describing processes causing adhesive seizing (tacking), one needs to consider the delay of the process of restoring metal oxides on metal surfaces (without oxides). This delay results from the fact that the oxidation process undergoes over time, regardless of the formation speed of metal oxides on clear surfaces. The oxidation process depends on the ability of penetration of the active oxygen contained in the operating fluid to the oxide-free surfaces of hydraulic pair elements (clear surfaces) [4, 9].

6. Conclusions

From the analyses and tests of the wear processes of hydraulic precise pairs, the following conclusions can be drawn:
1) Wear character and intensity of the hydraulic precise pairs depend mainly on the load of the pair's correlation, slide velocity and the movement length (friction route) of this pair's elements.
2) The dominating wear process in hydraulic precise pairs should be the wear due to oxidation. At the same time, there have to be conditions, in which during friction, the restoration of metal oxide structures on cooperating surfaces undergoes faster than abrasion. The domination of that wear process is conditioned mainly on maintaining the relative slide velocity of precise hydraulic pair's elements below the critical value during operation. After reaching the critical slide velocity, the adhesive seizing process is initiated and tacking processes of metal surfaces of the hydraulic pair start to dominate on friction surfaces.
3) Hydraulic slider pairs of control devices are periodically or constantly in the range of vibratory reciprocating movements. At the same time, the movement frequency and amplitude depend on the character of the pressure change (pulsation) of the operating fluid and change, depending on the operating range of the control unit. Due to vibratory micro-movements of the slider, the hydraulic pairs of control devices are exposed to the occurrence of adhesive seizing (tacking) of the slider pair elements' surface. The distinguishing properties of the adhesive seizing process conditions in slider pairs of hydraulic control devices at contact-vibration load are the small sizes of relative displacements of correlated surfaces of the slider pair, the size of the slide velocity and the speed of abrasion and formation of metal oxide layers on cooperating surfaces of the hydraulic pair. When the formation speed of metal oxide coatings on cooperating surfaces of the slider hydraulic pair is smaller than the speed of their seizing, the adhesive seizing (tacking) process begins.

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