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METHODS OF PREPARATION OF THE EXPERIMENT FOR INVESTIGATION OF UNIVERSAL JOINTS ON NEEDLE BEARINGS

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The main directions of development and improvement of performance data of universal joints needle bearings of transport technological machines are considered. The questions and tasks requiring the solution at the level of forming of new calculation procedures are specified. Modern achievements in researches of endurance failures and low-cyclic fatigue of needle bearings are considered. The main overview of the works performed in this direction is provided. The analysis of modern ideas of fatigue processes of needle bearings is given. The analysis of the current state of question on research of plastic deformation at static contact loading of needle bearings is given. Questions of forecasting of durability of needle bearings of universal joints are considered. The main questions connected with processes of forming of fatigue cracks in materials of needle bearings of universal joints in zones of power contact are considered. On the basis of the analysis of the used sources it was revealed that it is necessary to resolve the issues connected with improvement of performance data of universal joints needle bearings and questions of calculation of bearing capacity of power contact of rolling bearings and technology of receiving qualitative materials. For carrying out tests we used the test facility for universal joints allowing tests without overheat of system of braking due to cooling of working fluid and also improving operating conditions due to ensuring smoothness of regulation of braking torque. For measurement of roughness of surfaces the USB BV-7669M Profilograph profilometer was used. For measurement of hardness of surfaces of thorns of crosspiece of universal joints the HBRV-187,5 hardness gage was used. The technique of carrying out tests includes the following stages: marking of crosspieces of universal joints; measurement of roughness, hardness, geometry of crosspieces of universal joints; stage of tests; repeated measurements of roughness, hardness and geometry of crosspieces of universal joints; cutting of the studied universal joints and production of microsections for metallographic examinatons of active and passive surfaces of thorns of crosspieces of universal joints; processing of results of researches. The given technique of planning of experiments is intended for receiving experimental data of researches of universal joints at different stages of operation that will allow to estimate influences of errors of production on performance data of universal joints and to prove the reasons of formation of face and deep cracks.

Keywords: endurance failures, needle bearings, modern representations of researches, test facility, design of experiments, tests of joints.

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МЕТОДИКА ПОДГОТОВКИ ЭКСПЕРИМЕНТА ПО ИССЛЕДОВАНИЮ КАРДАННЫХ ШАРНИРОВ НА ИГОЛЬЧАТЫХ ПОДШИПНИКАХ

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Рассматриваются основные направления развития, улучшения и совершенствования рабочих характеристик карданных передач на игольчатых подшипниках транспортно-технологических машин. Указываются вопросы и задачи, требующие решения на уровне формирования новых методик расчёта. Рассматриваются современные достижения в исследованиях усталостных разрушений и малоцикловая усталость игольчатых подшипников. Приведен основной обзор выполненных работ в данном направлении. Дан анализ современных представлений об усталостных процессах игольчатых подшипников. Дан анализ современного состояния вопроса по исследованию пластического деформирования при статическом контактном нагружении игольчатых подшипников. Рассмотрены вопросы прогнозирования долговечности игольчатых подшипников карданных передач. Рассматриваются основные вопросы, связанные с процессами формирования усталостных трещин в материалах игольчатых подшипников карданных передач в зоне силового контакта. На основе анализа используемых источников было выявлено, что необходимо решить вопросы, связанные с усовершенствованием *рабочих характеристик карданных передач на игольчатых подшипниках, и вопросы расчёта несущей способности силового контакта подшипников качения и технологии получения качественных материалов. Для проведения испытаний использовался стенд для испытаний карданных передач, конструкция которого позволяет испытывать карданные передачи, исключая перегрев системы торможения за счет охлаждения рабочей жидкости, а также улучшить условия эксплуатации за счет обеспечения плавности регулирования тормозного момента. Для измерения шероховатости поверхностей использовался USB профилограф-профилометр БВ-7669М. Для измерения твердости поверхностей шипов крестовины карданного шарнира был использован твердомер HBRV-187,5. Методика проведения испытаний включает в себя следующие этапы: маркировка крестовин карданных шарниров; замер шероховатости, твердости, геометрии крестовин карданных шарниров; стадия испытаний; повторные замеры шероховатости, твердости, геометрии крестовин карданных шарниров; Разрезка исследуемых карданных шарниров и изготовление микрошлифов для металлографических исследований активной и пассивной поверхностей шипов крестовин карданных шарниров; обработка результатов исследований. Приведенная методика планирования экспериментов предназначена для получения экспериментальных данных исследований карданных передач на разных стадиях эксплуатации, которые позволят оценить влияния погрешностей изготовления на рабочие характеристики карданных шарниров и обосновать причины образования поверхностных и глубинных трещин.*

Ключевые слова: усталостные разрушения, игольчатые подшипники, современные представления исследований, испытательный стенд, планирование эксперимента, испытания шарниров.

Introduction. At the present stage of development of science and technology the problem of improvement of quality and competitiveness of universal joints needle bearings of different technological and hoisting-and-transport machines is essential for scientific and technical progress. But still many questions did not receive definite answer [1–15].

Now many researches are conducted and many methods of calculation of parts contact strength, durability and reliability are developed, but they do not offer accurate concepts and explanations of work of identical parts under absolutely identical conditions with different values of durability.

The analysis of the current state of science of wear lets know that without understanding of the process of wear creation of effective methods of fight against this phenomenon is impossible. The analysis of works [16–26] showed that hypothesis or the point of view were not always based on pilot experiments.

Due to the development of the reactive equipment, atomic-power engineering and creation of unique products and engineering designs in the different industries of mechanical engineering, the problem of low-cyclic durability of elements of designs becomes urgent in the 1950s. Due to the different processes of destruction of needle bearings at low and high levels of maximum voltages of cycle, we distinguish two types of fatigue: low-cyclic and multi-cycle. The low-cyclic fatigue is fatigue of material at which the fatigue damage or destruction happens at elasto-plastic deformation. The multi-cycle fatigue is fatigue of material at which the fatigue damage or destruction happens generally at elastic deformation.

Fatigue strength is an ability not to collapse under the influence of alternating loads during preset time of loading. It is supposed that the level of influences is such that the plastic deformations arising at the same time in metal in the course of loading are so small that it is difficult to find them, i. e. generally in the course of loading metal undergoes only elastic deformations. In case of the higher level of influences when plastic deformations become noticeable, and durability is rather small, there is low-cyclic fatigue [27].

At low-cyclic wear joint action of normal and tangent loadings at friction leads to the fact that the maximum tangent voltage arises not on the surface, but under the contact spot at small depth where damages gather and cracks are formed. If the material is fragile, the crack arises on its surface. Low-cyclic wear is observed during plastic deformation of surfaces (without cutting) of softer material by ledges the harder one. In places of such deformation side piles that at the subsequent passes can separate in the form of products of wear too are quite often formed [28].

Main part. Bearing blocks are the most important structural elements of machines and make the main part of frictional units. Failures of machines often happen because of failures of bearing blocks that limit durability of machines. Even at rather high-quality production of parts of bearing blocks, for example, of needle rolling bearing, the characteristic of universal joint can be unsatisfactory, and there may happen a sudden failure. By the failure we do not necessarily mean destruction of the rubbing (working) surfaces, but exit of one of characteristics of bearing blocks out of the allowed limits.

Bearing blocks of agricultural machinery fail generally because of the abrasive wear connected with hit of dirt and dust. The most widespread criterion of failure of the bearing blocks of the general application working in cars, tractors, pumps, reducers, machines, lifting-and-conveying machines is endurance failure. At the same time other characteristics, such as rigidity, level and range of vibration, antitorque moment, durability, etc. also are important for bearing blocks of special application.

The durability of separate parts of bearing blocks confirmed with bench tests does not guarantee sufficient durability of all node. The latter circumstance is connected with the fact that the loadings operating in node and actual temperature can significantly differ from the bench ones. Besides, assembly and mounting change gaps, tightness and form of working surfaces of bearing blocks. The contradiction between quality of bearing blocks and the bearing itself, which is shown in nodes with rolling bearings, is especially distinct [29–32].

At production of bearing blocks features of their work are often not considered. So, for example, universal joints needle bearings in parameters of undulation and roughness of working surfaces of the bearing not always conform to requirements of working conditions. Ball bearings for spindle of the machine have small limiting rapidity, which is caused by the considerable heat release from sliding friction and rolling friction leading to thermal expansion of internal ring and balls and thermal jamming (inadmissible increase of antitorque moment of shaft). The solution demands constructive changes in the bearing, namely decrease in heat release and increase in rapidity. It can be made by production of the bearing with large number of smaller balls. Such bearings developed by V. F. Grigoriev showed rather high rapidity. It is clear that at system approach to design of bearing blocks it is possible to provide required heat release and, as a result, required extreme rapidity of the bearing at design stage in advance.

Researches of plastic deformation of steel surfaces at static contact loading are given in R. G. Shtribek, S. V. Pinegin, A. Palmgren, D. Teybor's works. It was found out that at pure rolling of two cylinders under loading exceeding a certain level their surfaces are displaced rather central part in the direction of rotation as a result of plastic shifts in subsurface layer. U. Hamilton in the work showed that plastic shifts amass with quantity of cycles of loading. In K. Johnson's work it is shown that plastic deformation happens until Hertz tension does not become less than four limits of flowability at simple shift [11; 16; 26].

In the generalizing work by D. V. Orlov and S. V. Pinegina plastic deformation of the steel tempered parts at static loading, the pulsing contact and rolling under loading is investigated. Dependences of sizes of residual plastic deformation of surfaces on the level of tension, sizes and hardness are received. Calculations of tension taking into account plastic formings are carried out. The questions connected with justification of form of sample for carrying out material tests on contact fatigue are studied insufficiently.

The classical mechanics of contact interactions is connected, first of all, with the name of Heinrich Hertz. In 1882 he solved the problem about contact of two elastic bodies with the bent surfaces. This classical result is the cornerstone of mechanics of contact interaction also nowadays. Only a century later K. Johnson and other authors found the similar solution for adhesive contact (JKR – the theory).

Bases of the theory of contact voltages and deformations are developed by H. Hertz, N. M. Belyaev, A. N. Dinnik [11] and gained further development in a number of works of domestic and foreign scientists. Because of complexity of decisions of contact tasks the following assumptions were made: materials of bodies are homogeneous and isotropic; deformation happens in elastic limits and none of bodies receives plastic deformation; tangent loadings are absent in the zone of contact; both surfaces are absolutely smooth; the site of contact is small in comparison with the characteristic sizes of the compressed bodies; the hydrodynamic film between surfaces is absent. But at this stage of development only small part of assumptions takes place during the work of real parts, including contact task of H. Hertz which is the basis of engineering calculations of contact voltages and deformations.

Further progress of mechanics of contact interaction in the middle of the 20th century is connected with F. F. Bowden and D. Teybor. They were the first to show the importance of accounting of surface roughness of the contacted bodies. The roughness leads to the fact that the valid area of contact between the rubbing bodies is much less than seeming area of contact. These conceptions significantly changed the direction of many tribological researches. F. F. Bowden and D. Teybor's works caused emergence of number of theories of mechanics of contact interaction of rough surfaces.

The main works in the field of contact interaction are those of D. Arkhard who came to conclusion that at contact of elastic rough surfaces the area of contact is approximately proportional to normal force. The further important contribution to the theory of contact of rough surfaces was made by D. A. Grinvud and G. P. Villiamson. The main result of these works is the proof that the valid area of contact of rough surfaces in crude approximation is proportional to the normal force while characteristics of separate microcontact (pressure, the amount of microcontact) poorly depend on loading [31; 32].

The main role belongs to the bearing blocks working in the conditions of rolling under loading and its influence on operability of the hinge. However, despite the numerous researches worked in this direction new topical issues appear continually. The process of violation of kinematics of the bearing and its influence on operability of universal joints in general is not investigated fully. It is connected with damage of bodies and paths of rolling, influence and distribution of resistance to rolling on the areas of the rolling contact. Influence of thermal wear equally promotes change and destruction of paths of rolling and is the first-priority question demanding detailed consideration.

In actual practice during the work of needle bearings slipping of balls happens extremely seldom. Lubricant and other factors determine the size of external tangent loadings [16].

In I. Ya. Shtayerman's work number of space flat tasks was considered. Galin solved problems with friction and coupling of surfaces on contact taking into account the speed of deformation, anisotropy of material, variable on elasticity module depth, and also dynamic character of the phenomena on moving contact. N. I. Glagolev executed the solution of flat contact task taking into account friction forces and received the distribution law of normal and tangent loads with different distribution of sites of coupling and sliding on contact piece for the free and loaded with the moment wheel. The attempt is made to theoretically estimate wear of wheel and rail for case of plane-strain cylinders on empirical formulas of wear.

M. M. Saverin conducted an in-depth study of joint action of normal and tangent loads on tension at contact compression of the cylinder with the plane. In B. I. Kovalsky and M. M. Saverin's works tension at joint action of normal and tangent loads is deeply investigated [11].

Aspects of durability and hypothesis of destruction of materials at contact and cyclic loadings were described by A. Griffitson [4; 21] who explained discrepancy in durability of perfect and real brittle bodies with availability of defects like cracks. E. Orovan, G. I. Taylor and A. D. Polyani developed the theory of dislocations and suggested to connect decrease in durability and plasticity of solid bodies with availability of dislocations [21].

T. Ekobori offered a way of determination of durability and causes of destruction of solid body in which macrostress concentration from defects like dislocation pile-up is considered simultaneously [21]. At repeated and variable loading cracks arise in the most plastically deformed microvolumes of material, borders of grains detain plastic deformation, the fatigue crack develops on body of grain and does not extend on borders of grains, when crossing borders of grains it extends with the slowed-down speed, the cyclic load causes in grains of structure of metal of strip of loosening [22].

The concentrators of tension which are sources of development of contact and fatigue microcracks can be of two types. The first include localized defects such as scratches, grinding scratches, dents, areas of altered microstructure in the form of burns. To the second, we classify local discontinuities in the continuity and homogeneity of the metal in the form of nonmetallic inclusions, inclusions of carbides, pores, shells and other metallurgical defects. Influence of different concentrators of tension on contact fatigue is considered in works [5–8; 22–24]. When rolling under load, depending on the location of the stress concentrators that are most strongly influenced in specific conditions, the primary crack can occur on the surface of the part or under it. In this case, the surface crack will lead to the exfoliation of the metal particle and the resulting pit will be a new stress concentrator, which will cause the emergence of new microcracks, which lead to the separation of metal particles and the increase in the area of the crumpled site. This process is called pitting [16].

In case of development of fatigue crack from subsurface defect, it can be connected to the next microcracks. The trajectory and speed of its development depend on orientation of the microcracks lying close, and also on mechanical properties of the neighboring sites of metal. At the same time under surface several microcracks can develop. With cyclic loading, the crack that is in the most favorable conditions for its growth reaches the surface of the part and then the metal is chipping. And chipping depth from surface stress concentrators is several times greater than from surface defects [24].

In case of the so-called "the pulsing contact" primary fatigue cracks appear on surface of contour of spot of contact and extend deep into material. Extensive experimenttal data about arrangement of the possible centers of destruction at contact cyclic loading is given in work [24].

In P. Tardi and Ya. Stiklovari's works consider that all microcracks in bearings made of steel ShH15 develop from nonmetallic inclusions in area of coverage of Hertz maximum tangent voltages [7]. N. N. Kachanov [25], also leaning on experimental material, believes that fatigue cracks can arise not only at depth of action of the maximum tangent voltages, but also slightly higher or below it. N. N. Kachanov bases these reasons that emergence of the plastic shifts leading to fatigue cracks depends not only on the theoretical level of tangent tension, but also on the strength of the stress concentrators, the main ones being nonmetallic inclusions.

The idea of structure of solid bodies is revealed in the theory of dislocations [3; 18; 19]. Properties of metals and alloys are connected with emergence, movement and interaction of dislocations. At the heart of all ideas of durability and plasticity of metal materials data on their dislocation structure lie. Availability of dislocations explains sharp distinction between durability of real and reference metal. The dislocation structure in volume of real crystalline solid is implemented on the surface of body in the form of thin system of steps, hollows and ledges.

External mechanical influences define conditions for development of these or those leading processes in surface layers of metal of needle bearings. Under the influence of current changes serviceable condition of surface layer when material has the phase composition, structure and properties other than initial state forms. In the surface layer, that is in working order, there are processes the opportunities of which development depend on initial state of surface layer and operating conditions of needle bearings.

Depending on the nature of the processes happening during frictional unit operating time after the termination of its work in surface layer there are following residual changes: mechanical hardening or loss of strength; phase hardening or loss of strength without change or with change of chemical composition; change of microrelief of friction surfaces of needle bearings and tension of surface layer.

In modern representation the structure of surface layers of metal materials is multilayer [20]. After impact of shock impulse on the surface of material the central area of the place of blow will reflect acts of microjet current of material after passing of wave of deformation. After repeated impact of shock impulses, this zone will look like the hardened liquid with chaotic structure. Interaction of the central shock deformed area with the next objects of material can happen at the expense of rotational mechanisms to possible analogy to processes of current of viscous liquid in the oppressed layer. But at the same time, interaction of the central flow with laminar underlayer can be followed by emergence of whirlwinds. The vortex layer in metals can consist of several couples of vortex cords with counter rotation of cords in each couple. From outside rotational formations will kind of slide on laminar underlayer, representing structure with not equiaxial cells. Band and checkerboard structures are also rotational. The checkerboard structure has static deformation about 50–60 % and is represented by set of rectangular formations of different orientation. The band structure consists of rotational bands arranged in series and capable of moving deep into the material under the action of the stress field. Rotational structures are capable of changing one another according to the mechanism of kinetic phase transformations [20].

To date, these structures can be attributed to any mechanical action, including surface friction, but the finest outer layer will be so-called secondary structure, i. e.

strongly deformed and containing oxygen, sulfur and other elements.

At present, a lot of research has been done in this direction, but the issue of the mechanism of fatigue destruction is at the initial stage of development, which is confirmed by the search for the criterion of fatigue failure and the proposal of new solutions.

The quantitative assessment of contact fatigue is expressed in the number of loading cycles or in hours of operation before the occurrence of fatigue failure of surfaces. Cyclically changing contact stresses cause the formation of cracks and separation of material particles, surface destruction in the form of pits of chipping (pitting), cracks, peeling flaking [16].

The question is acute on the problem of modeling the processes of low cycle fatigue of needle bearings. A large number of phenomena accompanying this process are known, which can not be placed within the framework of any of the proposed theories. These include heat-activated accumulation of damages, wearing in of surfaces during friction, cyclicity of wear, kinetic phase transitions of defect structures, physico-chemical and structural modification of the material of the surface layer, etc.

As in the operation of needle bearing huge pressure on the actual spots of contact develops, formation of particles of wear at fatigue wear of needle bearings happens only after a set of cycles of contact interaction, causing periodic embrittlement and dispersion of surface layers. Each contact in surface layer causes irreversible changes of some diagnostic variable which identification is a necessary step in search of objective criterion of wear resistance of materials.

Studying of needle bearing destruction as the process developing during finite time and depending on loading speed is of great importance. In this case the criteria of classical fracture mechanics based on the theory of continuous environments cannot authentically reflect essence of real physical processes. With extremely high speeds of deformation, flashes of high local temperatures, concentration of high pressures there is not only smooth "shift" of phase point of condition of material in phase space, but also change of the leading mechanism of damageability. Therefore it is important to consider not only accumulation of damages, but also the mechanism which is responsible for specific way of destruction of bonds [33].

Particular interest in the mechanics of needle bearing failure with low-cycle fatigue is a time factor. It involves a wide range of tasks for forecasting the durability of structural materials and managing the life of products. It was noted in [34] that "the establishment of regularities in the evolution of the system requires the introduction of the time factor into the equation of the mechanical state". A lot of work has been devoted to the study of the relationship of time to strength parameters, but most of them are related to the study of the long-term strength of materials in creep, which is due to the applied importance of this problem. Since the rate of time flow in the system depends on the degree of influence of the deflecting factors [33; 34], the question of the zero value of the parameter arises. Is it possible to estimate the zero value of the system time in the same way as for temperature, pressure, entropy or other parameters. With what physical phenomenon the point of reference of time is connected at the analysis of durability of materials. An analysis of this problem shows that the time factor of modern science has not yet been sufficiently studied. The traditional perception of the longevity of the system as a time from the beginning of its loading to the moment of destruction is not physically justified.

Wear of universal joints depends on the physical and chemical and mechanical processes proceeding in contact. The kinematics of the movement of interfaces (sliding, roll, roll with sliding, roll under loading, etc.), structure and composition of surface and near-surface layers of materials, condition of lubricant layer, formation of surface connections, geometrical characteristics of contacting surfaces and their change in time has great influence on the process [16].

Due to the different processes of destruction of needle bearings at low and high levels of maximum voltages of cycle, we will consider questions of low-cyclic fatigue and formation of fatigue cracks in materials of needle bearings of universal joints, occurring at elasto-plastic deformation. It is supposed that the level of influences is such that the plastic deformations arising at the same time in metal in the course of loading are so small that it is difficult to find them, i. e. generally metal in the course of loading undergoes only elastic deformations. In case of the higher level of influences when plastic deformations become noticeable, and durability is rather small, there is low-cyclic fatigue. At low-cyclic wear joint action of normal and tangent loadings at friction leads to the fact that the maximum tangent voltage arises not on surface, and under contact spot at small depth where damages gather and cracks are formed [16; 28].

The endurance failure of surface layer occurs in the needle bearings which are exposed to long loading by variable efforts. Fatigue cracks arise on friction surfaces and extend deep into layer. Being gradually extended, small cracks form grid on certain limited or big sites of surface. Disclosure of cracks happens under the influence of the pulsating pressure of lubricant.

Crack, having reached the basis of antifrictional layer, changes the direction, extending on joint between the basis and layer, afterwards certain sites of surface layer chip. Chipping of large pieces of surface layer is followed by formation of surface "wounds" which are hammered with the wear products operating as abrasive. Flawing increases wear of friction surfaces, sharp edges make the cutting action, and near edges there is chipping of surface of material.

Cyclically changing contact voltages cause the surface destructions in the form of chipping poles called pitting. Formed abscesses ranging in size from a few hundredths of a millimeter to several millimeters increase during the operation of the friction unit, and surface peeling occurs.

In his works, I. V. Kragelsky developed an equation for frictional fatigue and developed a frictional fatigue model that takes into account processes at the level of influence of surface roughness, with relative sliding of rubbing bodies, a disruption occurs as a result of repeated deformation of the abraded material by the rigid micro-irregularities of the counterbody [16].

The process of accumulation of damages in sliding of bodies in a rolling condition under load has a certain staging. At first there is accumulation of elastic lattice distortions and increases density of dislocations. After achievement of critical density of dislocations there are submicroscopic cracks. Together with irreversible distortions of crystal lattice interatomic bonds are broken and separate microvolumes collapse [16; 28; 34].

By Ya. G. Panovko [16] researches it is established that in couples of friction at operation there are forced harmonic oscillations with frequencies up to 100 kHz and above. Sizes of vibratory frequencies are defined by the speed of relative movement and degree of roughness of contacting surfaces. Amplitudes of oscillation depend on physicomechanical properties of the contacting couples in conditions of loading. Forced oscillations are the cause of the appearance and development of fatigue cracks, resulting in destruction. Particular interest in the mechanics of needle bearing failure with low-cycle fatigue is a time factor. It involves a wide range of tasks for forecasting the durability of structural materials and managing the life of products.

Problem definition of research. The carried-out analysis showed that the problem of low-cyclic fatigue of needle bearings is studied insufficiently. All this detains development of the specified methods of calculation of parts that in turn affects rates of improvement of machine components designs, and, therefore, the over-all performance decreases at the expense of untimely exit of the equipment out of operation.

The question of the mechanism of physical aspect of metal fatigue and endurance failure of balls under the influence of temperature and fatigue wear is studied not completely and demands more careful studying as well as research of interrelation of primary endurance failures with dislocation of cyclically repeating or alternating tensions in material of parts.

Among other things, it is necessary to consider the influence of mechanical and thermal methods of surface hardening of parts on their fatigue contact strength with a complex alternation of stresses throughout the entire loading cycle during rolling under load.

Influence of radial, axial, angular fluctuations of balls of needle bearings is not studied sufficiently so far, as well as the issue of range of possible fluctuations of shaft of universal joints is not fully handled.

The problem of heat release and thermal conductivity is not fully addressed in the rolling of parts under load, and there is no system for predicting the temperature regimes of the operation of units and ways to reduce heat generation [1; 16; 17; 35–39].

For calculation of bearing capacity of modern designs and machine components, exposed in use to difficult complex of cyclically changing loadings, it is necessary to know stress and deformation fields in zones of the maximum strength, and also behavior of material during elasto-plastic cyclic deformation [40].

On the basis of this, the conditions for the emergence of limiting states are used – breaking strength, the appearance of unacceptable movement, etc. The most intensively developed direction when creating criteria for low-cycle strength under loading is the concept of equivalent parameters. According to this concept, choosing a corresponding equivalent parameter, a complex stress state leads to an equivalent linear stress state.

To assess the limiting state of materials in the theory of low-cycle fatigue, the criteria of four groups are used: deformation, force, energy and criteria based on the account of material damage. Deformational and energy criteria have become most widespread in the calculation practice [41].

In practice, equivalent parameters are widely used, which are a direct application of the criteria of plastic flow. A bright development of this approach was the work of M. Brown and K. Miller, who proposed two parameters for describing the low cycle fatigue: maximum shear deformation and normal deformation in the plane of maximum shear. At present, there is a significant number of modifications to this approach. Generalizing the work in this direction, apparently, is the work of A. Mackind and K. Neal in which a technique is proposed for constructing the function of destruction and a description on its basis of curves of equal durability. The authors have shown that all the criteria previously proposed in the framework of the equivalent approach are special cases of the destruction function [42].

Deformation criteria are based on the fact that under a rigid loading regime, the quasistatic fracture region is absent on the low-cycle fatigue curves, therefore the limiting state of the material can be estimated by the amplitude (swing) values of the total deformation, its elastic or plastic components. However, if for uniaxial or proportional deformation these criteria are sufficiently effective and simple, then for multiaxial low-cycle loading they do not always give acceptable results. In accordance with energy criteria, the limiting state in the material occurs when the total energy associated with its hardening reaches a critical value. In this regard, the energy approach to the assessment of fatigue damage and the destruction of metals is more general, because it uses as a measure of material damage the specific scattered energy or the specific work of plastic deformation per loading cycle. The latter circumstance is important when considering biaxial or multiaxial fatigue, when cyclic trajectories with the same range of deformations, but with different cycle shapes, correspond to different levels of durability. The practical use of energy criteria with respect to disproportional deformation causes specific requirements for the choice of a theory of plasticity for a more accurate prediction of the elastoplastic hysteresis loops, and it involves some difficulties in calculating the specific work of plastic deformation.

Attempts of overcoming shortcomings of deformation and power approaches led to development of the modified deformation criteria allowing considering both influence of amplitude of deformations, and the additional hardening that is strongly expressed at disproportionate deformations. The present work is devoted to the analysis of recently published experimental results on the behavior of various metallic materials under biaxial low-cycle fatigue and the development of approaches for creating an effective modified deformation criterion on their basis [41].

The problem of low-cyclic fatigue of elements of machines and designs which arose in connection with intensification of operation of products in the conditions of high thermomechanical loading at the quasistationary nature of repeated static power and temperature influences develops in relation to problems of assessment of endurance and durability on the basis of deformation interpretation of criteria of destruction [43].

Problem of low-cyclic fatigue of the bearing elements of designs and machine components with the broad range of temperatures and speeds of loading in relation to low-cyclic fatigue (without taking into account the temperature-time factor) and long cyclic durability (taking into account temperature and time factor), including two main directions: research of kinetics of stress fields and deformations in the zones of the maximum strength defining places of the accelerated accumulation of damages and destruction; studying of properties of materials by number of cycles and deformation time [44].

Proceeding from the aforesaid it is necessary:

1. Carrying out tests of universal joints at different stages of operation (breaking-in, normal operation, failure).
2. Errors of production impact assessment on performance data of universal joints.
3. Justification of the reasons of formation of face and deep cracks.

Description of the equipment. For laboratory tests the stand for tests of universal joints will be used, the design of the stand is presented in fig. 1, 2. The stand consists of the electric motor *1* which output end is connected to the technology transfer *2* connected to the tested universal joint *3*, mounted on the main frame *4*. The output shaft of universal joint *3* is connected to input shaft of the distributing reducer *5* mounted on additional frame *6*. The device of loading is hydraulic and represents hydraulic pump *7* which shaft is attached to output shaft of distributing reducer *5*. The input channel of hydraulic pump *7* is connected to hydraulic tank *8* with working fluid, and its output channel is attached to the input channel of throttle *9* regulating loading. Between the throttle and hydraulic pump the manometer *10* calibrated in terms of braking torque and the safety valve *11* for release of excessive pressure in hydraulic tank *8* are installed. The output channel of throttle is connected to hydraulic tank, via the heat exchanger *12*.

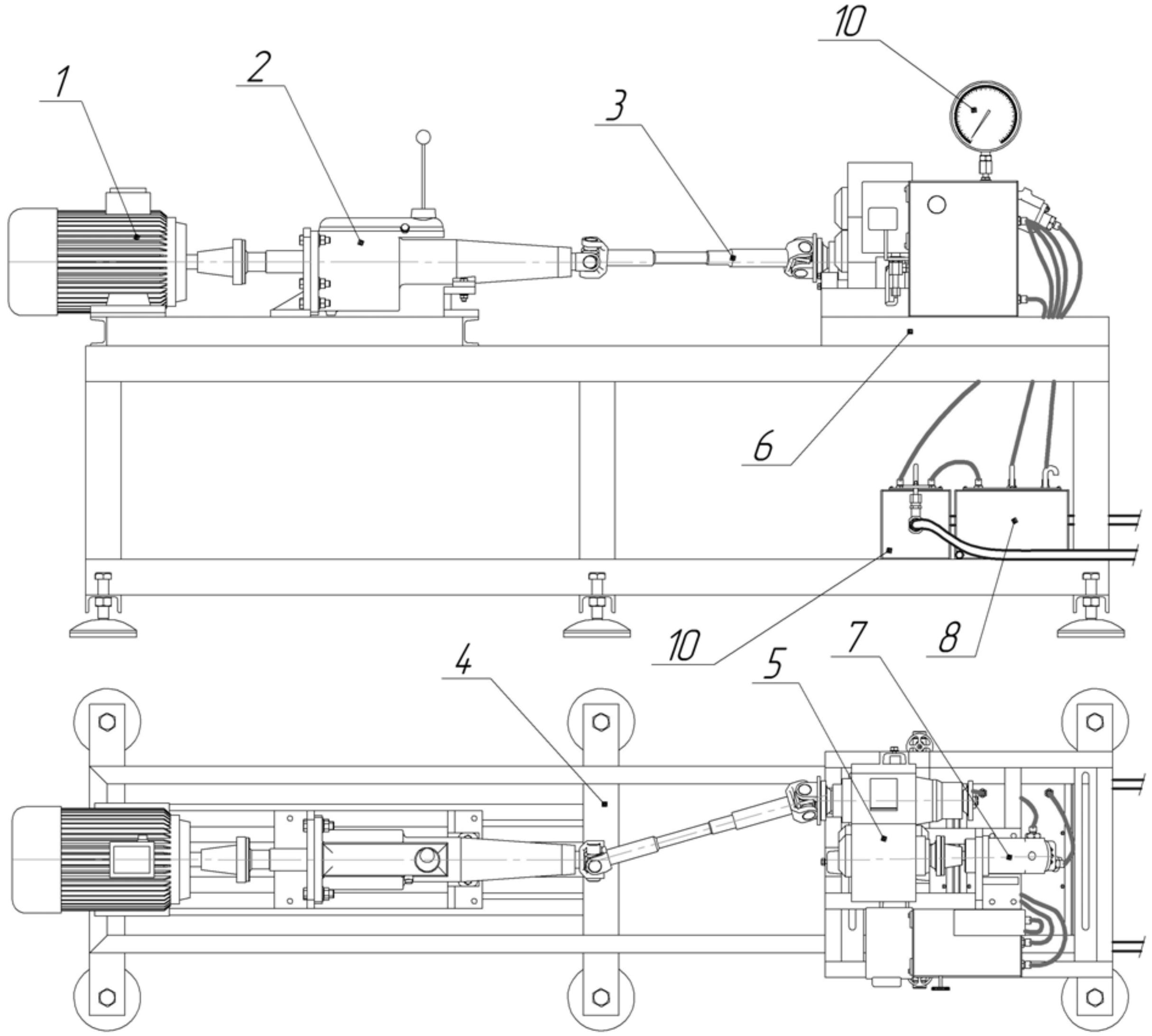

Fig. 1. The stand for research of universal joints

Рис. 1. Стенд для исследования карданных передач

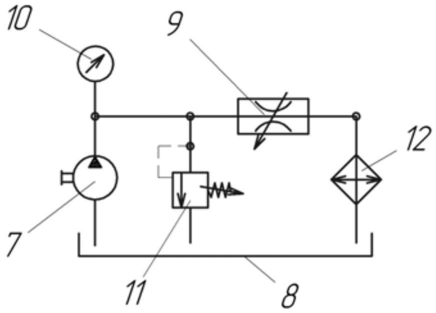

Fig. 2. The hydraulic scheme of the stand for research of universal joints

Рис. 2. Гидравлическая схема стенда для исследования карданных передач

The stand works as follows: the torque from the electric motor *1* is transferred to the tested universal joint *3* through technology transfer *2*, hydraulic pump *7* at the same time transfers to the tested universal joint the braking torque created and regulated by throttle *9*, value of braking torque is defined with the help of the manometer *10* calibrated in terms of braking torque. With an excess of operating pressure, the safety valve *11* is activated to prevent a jump in the set pressure of the hydraulic fluid in the hydraulic system that releases excess pressure into the hydraulic tank *8*. The heat exchanger *12* cools the working fluid.

The size of corner of break of universal joint is change by movement of the cross movable frame having the nonius by means of which the corner of break of universal joint for the corresponding length of universal joint is exposed.

The design of the offered stand allows to test universal joints, excepting overheat of system of braking due to cooling of working fluid, and also to improve operating conditions due to ensuring smoothness of regulation of braking torque. The stand offers simplicity of design and system of setup of braking torque by means of adjustable throttle and the manometer of pressure of working fluid calibrated in terms of braking torque [45–52].

For measurement of roughness of surfaces the USB BV-7669M Profilograph profilometer was used. The profilograph profilometer is intended for registration, the analysis of profile and measurement of parameters of roughness, outer and inner surfaces which section represents straight line to the planes of measurement. Before use calibration of the sensor, i. e. setup of sensitivity of measuring channel of the sensor by means of sample of the Ra parameter, adjusting with rated value, which is part of the profilometer was carried out.

For measurement of hardness of surfaces of thorns of crosspiece of universal joints the HBRV-187.5 hardness gage was used. The hardness gage is intended for determination of hardness by Rockwell, Brinell and Vikkers's methods. The hardness gage is widely used at the enterprises of mechanical engineering and metallurgy, laboratories of higher education institutions and research institutes for determination of hardness. The hardness gage consists of frame, the main lever mechanism, the mechanism of loading and unloading, the optical measuring screen, the mechanism of the choice of loading and the mechanism of raising of worktable. The frame is the closed body in which there are all mechanisms, except table, screw rod and part of the main rod. The hardness gage is the optical measuring instrument mainly by Rockwell's method. The device transforms depth of cup to units of hardness and directly displays on the projection screen which is on the front panel of the hardness gage. The surface of the studied sample should be equal, smooth and pure; there should not be traces, pollutants, stratifications, cracks, dredging, etc. on it. The bearing surface of the sample and worktable also should be pure for achievement of the best contact. The surface of the sample should be flat, the radius of curvature should not exceed 15 mm.

The technique of carrying out tests includes the following stages:

1. Marking of crosspieces of universal joints. The arrangement of crosspieces on shafts was recorded on lubricators, which serve to determine the leading and trailing spikes of the joint of the universal joint (fig. 3).

The account of numbers of thorns of crosspiece of universal joints begins with the hinge face where the lubricator is, and proceeds in ascending order clockwise.

2. Measurement of surface roughness, hardness and geometry. Surface roughness; geometrical sizes of universal joints; hardness of universal joints were measured before tests.

The roughness of surfaces was measured according to the scheme in fig. 4 on every thorn of crosspiece No. *1–4* from four points t. *1–4* in a straight line along thorn axis. Ra – arithmetic average deviation of profile and Sm – average step of roughnesses of profile of surface roughness were received as parameters of surface roughness values.

We measure the geometrical sizes of universal joints according to the scheme in fig. 5, these are diameters of thorns of crosspiece of d_i, length between end faces of thorns of crosspiece is of *l*13 and *l*24, diameters of glasses of needle bearings of D_i.

We measure the hardness of universal joints on each thorn of crosspiece (fig. 4) in current t. *1*.

3. Testing stage. According to researches [16] the stage of breaking-in comes to an end in the range from 1 to 5 hours of universal joints operation therefore we will use time intervals from 1 o'clock in each hour, i. e. to

carry out tests on the first universal joints – 1 hour, on the second – 2 hours, etc. After detection of changes (transition to stage of low-cyclic fatigue from stage extra earnings), we will investigate the received interval with more exact step.

4. Repeated measurements of roughness, hardness, geometry according to item 2.

5. Cutting of the studied universal joints and production of microsections for metallographic examinatons of active and passive surfaces of thorns of crosspieces of universal joints according to the scheme (fig. 6)

6. Processing of results of researches by method of the smallest squares, which based on minimization of the sum of squares of deviations of some functions from required variables and assessment of errors of measurements, creation of curve of fatigue (Veller's curve) (fig. 7).

The problem of preliminary experiment consists in check:

1. Operability of test stands [45–47] of author's development and possibility of carrying out tests of universal joints at different stages of operation [53–54] (breaking-in, normal operation, failure); assessment of impact of errors of production on performance data of universal joints for justification of the reasons of formation of face and deep cracks.

2. Sensitivity of systems and elements of the test stand [55].

3. Carrying out preliminary tests for verification of the plan of tests and investigation of significant levels and factors, the accuracy of levels and classes of the test stand, identification of error of measurements.

4. Dependences of the constructive modes and parameters of criterion function, such as torsional moment and braking which are not connected with long-run, resource tests, so-called kinematic sizes.

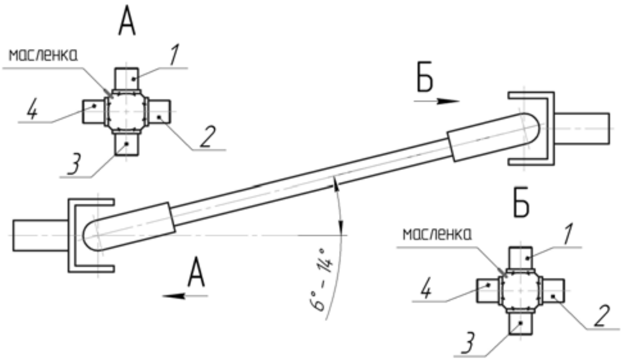

Fig. 3. The scheme of installation of the tested joints of the prop shaft

Рис. 3. Схема установки испытуемых шарниров карданного вала

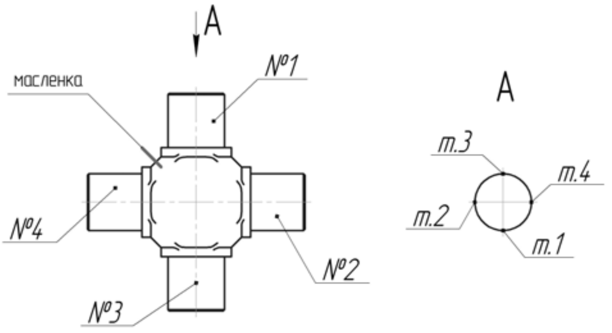

Fig. 4. Scheme for measuring roughness and hardness of surfaces

Рис. 4. Схема измерения шероховатости и твердости поверхностей

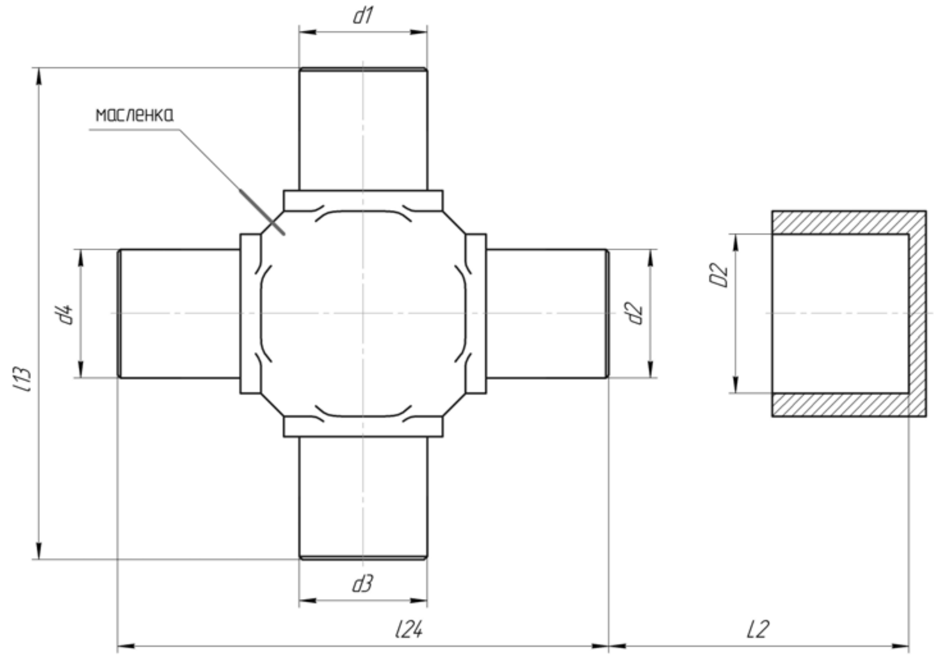

Fig. 5. Scheme of measurement of sizes of universal joints

Рис. 5. Схема измерения размеров карданных шарниров

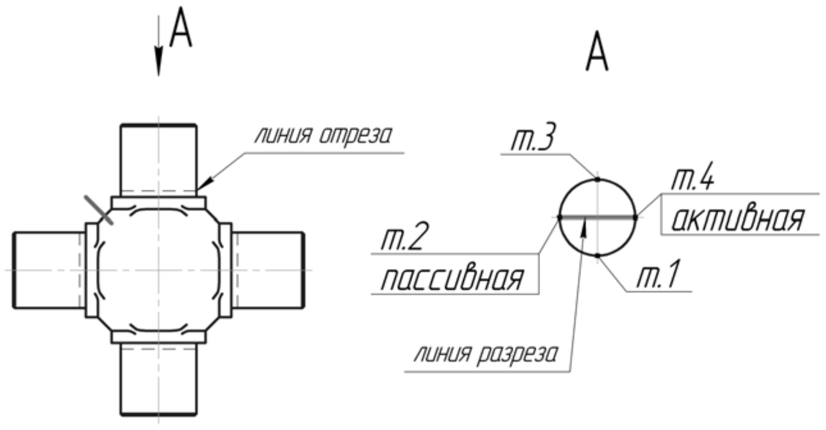

Fig. 6. Scheme of cutting of the studied universal joints for production of microsections

Рис. 6. Схема разрезки исследуемых карданных шарниров для изготовления микрошлифов

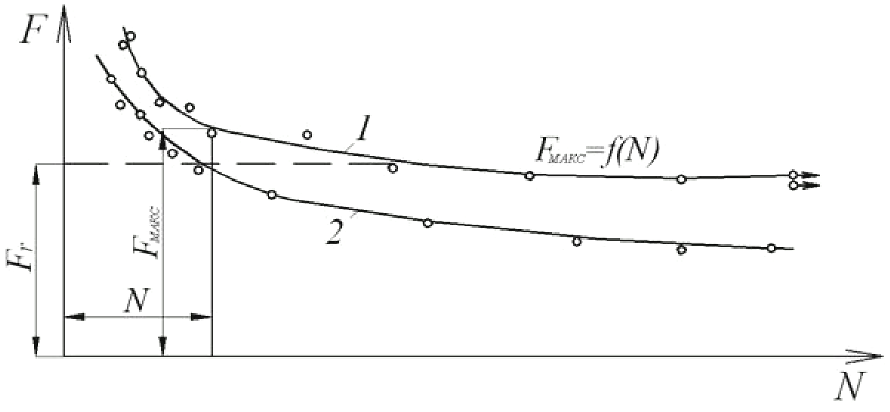

Fig. 7. Fatigue Curve (Veller's curve)

Рис. 7. Кривая усталости (кривая Веллера)

Table 1

Summary data table of hardness of universal joints

Number of the hinge	Hardness, HRC			
	1 thorn	2 thorn	3 thorn	4 thorn
1	56.5	54.5	54.5	56.0
2	58.5	58.5	58.5	58.5
3	53.5	53.5	53.5	53.5
4	55.0	56.0	56.5	56.0
5	59.0	59.0	58.5	59.0
6	60.5	60.5	63.5	61.5

For performance of preliminary experiment, measurements according to technique of carrying out tests were carried out, results of measurements are given in tab. 1–3.

Conclusion. In conclusion we will note that the most essential in all given work, is that the low-cyclic fatigue of needle bearing, process of forming of fatigue cracks in materials of needle bearings of universal joints at low-cyclic fatigue of needle bearings is topical issue and demands additional research in this direction. Many shortcomings of domestic machines, their low resource are connected with underestimation of dynamics during the calculating, design and operation. Physical processes at rolling friction of needle bearing are caused by patterns of interaction of solid bodies, at elastic and plastic deformation of microroughnesses of surfaces, heat transfer, adhesion and hydrodynamics of lubricant. The carried-out analysis showed that the problem of "low-cyclic" fatigue of needle bearings is studied insufficiently, and many shortcomings of domestic machines, their low resource are connected with underestimation of dynamics during the calculating, design and operation. Physical processes at rolling friction of needle bearing are caused by patterns of interaction of solid bodies, at elastic and plastic deformation of microroughnesses of surfaces, heat transfer, adhesion and hydrodynamics of lubricant.

Table 2

Summary table of measurements of roughness measurements on the surfaces of universal joints

Parameter	Thorn № 1				Thorn № 2				Thorn № 3				Thorn № 4			
	т. 1	т. 2	т. 3	т. 4	т. 1	т. 2	т. 3	т. 4	т. 1	т. 2	т. 3	т. 4	т. 1	т. 2	т. 3	т. 4
	Crosspiece 1															
Ra	0.735	0.767	0.621	0.759	0.669	0.745	0.708	0.715	0.614	0.644	0.589	0.623	0.673	0.642	0.595	0.621
Sm	0.085	0.078	0.065	0.075	0.078	0.081	0.078	0.077	0.071	0.071	0.069	0.067	0.071	0.067	0.070	0.066
	Crosspiece 2															
Ra	0.461	0.454	0.454	0.482	0.412	0.372	0.478	0.451	0.393	0.413	0.335	0.401	0.504	0.419	0.454	0.508
Sm	0.057	0.065	0.072	0.059	0.060	0.060	0.063	0.058	0.062	0.075	0.073	0.062	0.062	0.070	0.073	0.070
	Crosspiece 3															
Ra	0.375	0.472	0.397	0.420	0.381	0.423	0.447	0.409	0.384	0.634	0.421	0.394	0.326	0.323	0.390	0.404
Sm	0.058	0.062	0.071	0.063	0.068	0.061	0.060	0.068	0.065	0.053	0.072	0.062	0.056	0.062	0.061	0.061
	Crosspiece 4															
Ra	0.863	0.662	0.759	0.896	0.708	0.659	0.646	0.705	0.759	0.689	0.630	0.644	0.743	0.727	0.887	0.835
Sm	0.077	0.075	0.090	0.078	0.079	0.066	0.066	0.078	0.066	0.081	0.069	0.067	0.066	0.068	0.072	0.075
	Crosspiece 5															
Ra	0.381	0.571	0.599	0.450	0.406	0.410	0.498	0.500	0.458	0.726	0.451	0.451	0.382	0.394	0.484	0.538
Sm	0.067	0.081	0.073	0.081	0.073	0.070	0.067	0.078	0.073	0.074	0.060	0.070	0.071	0.070	0.076	0.090
	Crosspiece 6															
Ra	0.372	0.310	0.408	0.271	0.603	0.518	0.334	0.345	0.414	0.337	0.426	0.461	0.379	0.515	0.310	0.322
Sm	0.080	0.070	0.058	0.059	0.072	0.067	0.064	0.068	0.081	0.068	0.079	0.062	0.064	0.072	0.069	0.066

Table 3

Summary table of measurements of dimensions of universal joints

Diameter of the bearing, mm.				Diameter of the bearing, mm.				The size between end faces of thorns, mm.	
$d1$	$d2$	$d3$	$d4$	$D1$	$D2$	$D3$	$D4$	$l13$	$l24$
Crosspiece 1									
16.29	16.28	16.29	16.29	16.30	16.33	16.34	16.35	79.96	79.95
Crosspiece 2									
16.28	16.28	16.29	16.29	16.36	16.35	16.32	16.33	79.98	79.99
Crosspiece 3									
16.28	16.29	16.29	16.29	16.35	16.34	16.33	16.35	80.01	80.01
Crosspiece 4									
16.29	16.29	16.29	16.29	16.28	16.32	16.35	16.33	79.86	79.95
Crosspiece 5									
16.61	16.61	16.60	16.60	16.67	16.64	16.72	16.63	80.01	80.00
Crosspiece 6									
16.61	16.61	16.60	16.61	16.67	16.70	16.63	16.70	79.99	79.99

On the basis of the analysis [1–26] it was revealed that it is necessary to resolve the issues connected with improvement of performance data of needle bearings universal joints and questions of calculation of bearing capacity of power contact of rolling bearings and technology of receiving qualitative materials. The given technique of planning of experiments is intended for receiving experimental data of research of universal joints at different stages of operation which will allow to estimate influences of errors of production on performance data of universal joints, including author's developments [54–59] and to prove the reasons of formation of face and deep cracks.

As a result of carrying out preliminary experiment dependences of the constructive modes and parameters of criterion function, such as torsional moment and braking which are not connected with long-run, resource tests, so-called kinematic sizes will be received. Operability of test stands [45–47] of author's development and possibility of carrying out tests of universal joints at different stages of operation is checked (breaking-in, normal operation, failure); impact assessment of errors of production on performance data of universal joints for justification of the reasons of formation of face and deep cracks. Sensitivity of systems and elements of the test stand is checked. The plan of tests and technique of tests for determination of significant levels and factors, accuracy of levels and classes of the test stand, identification of error of measurements are checked.

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