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Study of the Stress-Strain State of the Surface Layer During the Strengthening Treatment of Parts

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Abstract

The paper presents experimental studies and obtained statistical models of the influence of processing modes on the quality of the surface layer and cyclic durability of reinforced machine parts. It was established that the main influence on the strengthening effect, the depletion of the plasticity reserve of the metal and the formation of residual stresses are exerted by the effective gap of the cutter, the effective tension and the profile radius of the roller. The results showed that dimensional combined running-in ensures high cyclic durability of strengthened parts under conditions of multi-cycle fatigue load, which reaches 8 million cycles, which is 3.5 times greater than the durability of a non-reinforced part and 1.5 times - the durability of a part strengthened by surface plastic deformation Studies have shown that the greatest cyclic durability of the part is ensured at the minimum values of the effective cutter gap, the maximum values of the profile radius and the value of the effective roller tension of 0.6 mm, which corresponds to the degree of exhaustion of the plasticity reserve by processing with dimensional compatible rolling $\Psi \approx 0.65$. On the basis of the results of theoretical and experimental studies, a methodology and algorithm for the design of processing technology by dimensional combined running-in were developed. A computer program has been developed that allows you to calculate the quality of the surface layer and cyclic durability of the part based on the specified modes, as well as to assign rational processing modes that ensure the specified quality of the surface layer and cyclic durability. Based on the results of research, a technological process of strengthening processing of machine parts by combined dimensional running-in has been developed, which allows forming compressive residual stresses in the surface layer of the processed part, as well as increasing productivity up to 2 times while maintaining or improving the specified quality parameters of the surface layer of the processed part.

Key words: dimensional compatible running-in, stress-strain state, strengthening treatment, surface plastic deformation, residual stresses

Introduction

The urgent task of modern mechanical engineering is to ensure the durability of machine parts, which is largely determined by the quality of the surface layer (SL). The surface layer is formed during the entire technological process, while the phenomenon of technological inheritance (TI) plays an important role.

Improving the quality of the surface layer is possible on the basis of improving the methods of strengthening treatment, as well as identifying the regularities of the TS and their influence on the operational durability of the part, including under the conditions of the application of fatigue loads.

One of the ways to improve the quality of machine parts is the application of technological processes based on combined methods of surface plastic deformation (SPD), including the method of dimensional simultaneous running-in (DSR). The peculiarity of DSR is the original scheme of operation of cutting and deforming tools, according to which, the cutter cuts the plastic wave of metal that occurs in front of the deforming rollers.

This method ensures high accuracy of machine parts, parameters of roughness and strengthening of the surface layer when processing a wide range of important parts, such as rods, shafts, axles, etc., made of reinforcing structural materials and operating under conditions of application of cyclically alternating loads.

In relation to such processes of strengthening treatment, the development of an analytical apparatus is relevant, which allows to calculate the operational durability based on taking into account the entire complex of inherited properties of the surface layer, since the appearance of new materials and the complication of machine operating conditions require a reduction in the terms of structural and technological preparation of the organization by reducing experimental work [1].

Solving this problem is possible on the basis of the disclosure of the consequent physical regularities, both the formation of the state on top of the next layer during processing by dimensional combined rolling, and the transformation of this state during operational fatigue loading of the part. For the study of such regularities, the apparatus of the mechanics of technological inheritance is adapted, based on the accounting of the continuous accumulation of deformations, the exhaustion of the reserve of plasticity and the formation of residual stresses by the metal of the surface layer at the stages of the life cycle (LC) of machine parts, including at the stage of operational fatigue load. The application of the TI mechanics apparatus allows to describe in uniform terms and categories the physical nature of the behavior of metal at the stages of metallurgy and to bring the results of research into a form convenient for engineering use.

Thus, the wide possibilities of the method in terms of ensuring quality and accuracy, on the one hand, and the lack of technological recommendations for ensuring the cyclic durability of strengthened critical parts, on the other hand, restrain the wide application of DSR in industry.

Taking into account the growing requirements for quality and the need to ensure the durability of parts during operation, this work, aimed at the development of analytical apparatus and methods of designing technological processes of strengthening treatment, is relevant.

Literature review

The works of P.G. Alekseeva, M.A. Balter, Y.M. Baratsa, V.F. Bezyazichny, V.M. Braslavskyi, M.S. Drozda, M.M. Zhasimova, S.A. Zaides, A.V. Kyrycheka, E.H. Konovalova, I.V. Kudryavtseva, A.G. Lazutkina, E.M. Verkhivka, L.I. Markus, L.G. Odintsova, D.D. Papsheva, V.V. Petrosova, V.N. Poduraeva, Yu.G. Proskuryakova, O.A. Rosenberga, E.V. Ryzhova, V.M. Smilyanskyi, A.H. Suslova, L.A. Khvorostukhina, P.A. Chepy, P.S. Chistoserdova, L.M. Shkolyara, Yu.G. Schneider, D.L. Yudina, P.I. Lizard and others [2].

One of the effective methods of combined SPD is dimensional run-in, the technological capabilities of which are explored in the works of V.M. Smilyanskyi, V.Yu. Blumenstein, V.A. Vasylieva, V.B. Ignatov and T. Niklevich [3].

The DSR method is quite well studied in terms of ensuring the accuracy and quality of the surface layer. In particular, it was established that it allows to provide within wide limits such quality parameters as roughness (Ra = 0.04...0.8 μm), depth (h = 0.5...15 mm) and degree (δ = 0.2...0.8) strengthening when creating favorable compressive stress patterns.

However, at the same time, the possibilities of dimensionally compatible running-in to ensure the cyclic durability of parts remain unestablished. These capabilities are especially relevant for a wide range of parts operating under fatigue load conditions.

To solve this problem, an analysis of methods for ensuring the quality and durability of strengthened machine parts, features of the formation of final stresses during strengthening processing, as well as an analysis of approaches to accounting for the phenomenon of technological inheritance, outlined in the works of V.I. Averchenkova, I.A. Birgera, V.Yu. Blumenstein, A.S. Vasylieva, A.M. Dalsky, A.I. Kondakva, I.V. Kudryavtseva, A. A. Matalin, A.N. Ovsienko, A.V. Podzeya, E.V. Ryzhova, V.M. Smilyanskyi, A.H. Suslov The formulation of the scientific task of developing a methodology for the design of technological processes of strengthening processing by the RSO method, ensuring the cyclic durability of machine parts and taking into account the appearance of technological inheritance, has been completed [4].

It was established that the apparatus of the mechanics of technological inheritance, developed by V.Yu. Blumenstein, is adapted for solving such a task in the framework of which the formation and transformation of the state of the surface layer at the stages of mechanical processing and subsequent operational fatigue load are considered as a single continuous process of accumulation of deformation and exhaustion of the reserve of plasticity of the metal of the surface layer.

Along with traditional quality parameters, the used apparatus of the mechanics of technological inheritance allows for a thorough description of the regularities of the formation and transformation of the properties of the surface layer at the stages of mechanical processing and subsequent operational fatigue loading in the categories of integral parameters that are uniform for all stress stages: the degree of shear deformation Λ, the degree of depletion plasticity reserve Ψ and residual stress tensor [$T\sigma_{ост}$]. The device allows you to take into account the influence of the accumulated properties of the surface layer on the cyclic durability of the part; at the same time, the latter is understood as the number of load cycles until the plasticity reserve of the metal of the surface layer is completely exhausted and the appearance of a fatigue crack. To calculate the degree of depletion of the plasticity reserve Ψ, the Kalpin-Filippov criterion is used, which takes into account the partial "healing" of the metal defect and the restoration of the plasticity reserve in the zone of change in the sign of deformation [5].

The analysis showed that the use of the apparatus of the mechanics of technological imitation allows to establish the physical regularities of the formation of the surface layer, the processes that occur during the processing of DSR in the deformed hearth, as well as the regularities of the influence of these processes on the cyclic durability of the part.

Purpose

The purpose of the research is to increase the durability of machine parts strengthened by dimensionally combined running-in based on taking into account the inherited properties of the surface layer.

Research methodology

In order to assess and manage the state of the surface layer in order to ensure the specified cyclic durability of DSR-treated machine parts, the apparatus of the mechanics of technological inheritance was adopted, according to which:

- during the processing of DSR, there is an accumulation of deformations and the exhaustion of the reserve of plasticity, which leads to the formation of a surface layer with defined quality parameters: depth and degree of strengthening, roughness and residual stresses;
- in the process of further operational fatigue loading, the process of accumulation of deformations, depletion of the plasticity reserve and relaxation of residual stresses continues, which leads to a continuous transformation of the loaded state and a change in the degree of strengthening of the surface layer;
- when the limit deformations accumulate to the level of Λp, the plasticity reserve is completely exhausted ($\Psi = 1$). This state corresponds to complete relaxation of residual stresses ($[T\sigma_{ост}] = 0$) and the appearance of an initial fatigue crack.

In order to structure, systematize and further solve the given problem, a structural-analytical model of the formation of the parameters of the mechanical state of the metal of the surface layer of the part at the stage of dimensional combined running-in was developed, taking into account the phenomenon of technological imitation in the context of ensuring the necessary cyclic durability [6].

The model, built on the basis of CALS - technologies, is based on the idea of the considered process as an information system. The function "Manage the parameters of the mechanical state of the surface layer of the metal at the DSR stage in order to ensure the given cyclic durability of the part" was selected as a high-ranking function. The decomposition of the context diagram made it possible to identify the main parameters for the purpose of controlling the mechanical state of the surface layer and to describe them by a system of kinetic equations.

Research results

The method of dimensional combined running-in is based on plastic wave formation; at the same time, the processing is carried out by two or three rollers, rigidly adjusted to a certain size of the processing of the part. The principle is the presence of a cutter in the zone of wave formation, which partially or completely removes the plastic wave. The tensions of the deforming rollers significantly exceed those adopted for SPD and reach values of 1 mm, however, the destruction of the surface does not occur due to the removal of part of the metal by the cutter in the area of the top of the plastic wave.

When solving the problem of mechanics of cyclic durability, it was accepted:

1. During operation, the part is subjected to multi-cycle fatigue symmetrically changing stress with a scheme of cantilever bending with rotation, fatigue (operational) and residual stress tensors are specified in the Cartesian coordinate system, while the numerical values of the residual stress components decrease in proportion to the number of cycles in accordance with the selected by the law of relaxation.
2. Accumulation of limit deformations, complete exhaustion of the reserve of plasticity and nucleation of a fatigue crack occurs at some point of probable destruction, which can be located both on the surface and at some distance from it; at the same time, there is no point drift in the process of fatigue loading.
3. The end of the stage of cyclic durability corresponds to a certain limiting degree of hardening and hardness (microhardness) of the surface layer at the point of probable destruction, characteristic of the given material, processing modes and load conditions.

Experimental studies were carried out on a 1K62B lathe and screw-cutting machine, equipped with an installation for RSO, as well as on a model 16K20F3 lathe, equipped with a special installation for processing RSO of fatigue samples. The ranges of variation of the processing mode parameters were: feed (S) - 0.07...0.7 mm/rev, part rotation frequency (n) - 100...1200 rpm, profile radius of the roller (R_{pr}) - 2...15 mm , estimated roller tension (h_p) - 0.1...1 mm, actual gap (a_d) - 0...0.2 mm, actual tension (h_d) - 0.05...0.9 mm [7].

The actual geometric parameters of the deformation center were determined by profilography and further processing of the obtained profilograms. To increase efficiency and automate calculations, an algorithm and a program for processing OD profilograms were developed. Their task is to translate the graphic image of the profilogram into the numerical values of the points that make up the OD contour.

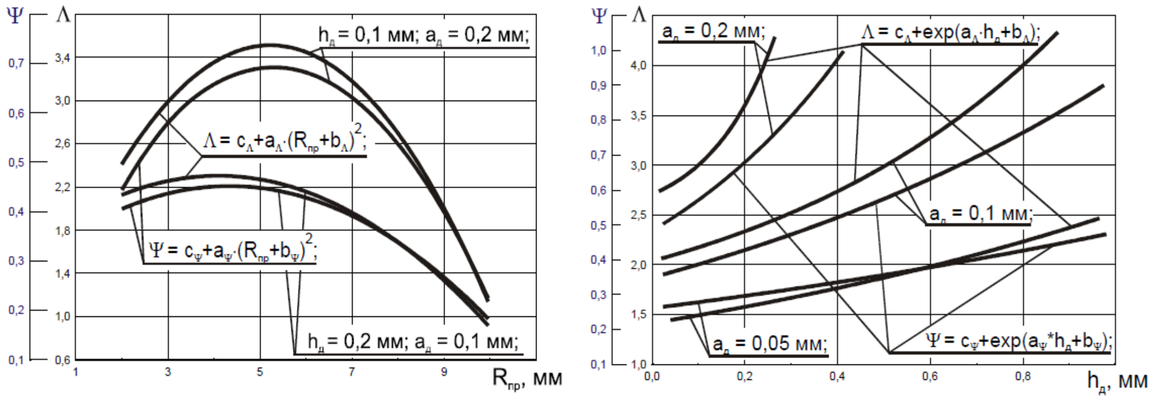
Experimental samples were made from steel 45 of one delivery. In order to localize the fatigue crack initiation point, the working surface was made in the form of a combination of a cylindrical part and a fillet. The working part of the fatigue samples, which has a diameter of 15 mm, was subjected to DSR processing on a 16K20F3 machine with different modes. For each series, a sample was made - a witness, on which fixation of the center of deformation was carried out [8]. Based on the obtained deformation rates, the actual parameters of the processing mode, as well as the parameters of the mechanical state of the surface layer, were calculated.

The cyclic durability of the samples was determined on the basis of the proposed calculation-analytical model and fixation of the change in the microhardness of the surface layer during cyclic loading. The distribution of microhardness along the depth of the surface layer was determined in the dangerous section of the samples after stressing with a fixed number of cycles, while the witness samples made it possible to determine the initial distribution of microhardness before fatigue stress [9].

The relationship revealed as a result of experimental and analytical research explains more than 90% of the entire dispersion of experimental data, the relative error of determination does not exceed 15%.

The analysis showed that the actual incisor clearance has the predominant influence on the deformation parameters (Fig. 1, a, b). With a relatively small increase in it, Λ and Ψ grow significantly, since in this case a more deformed metal forms the machined surface.

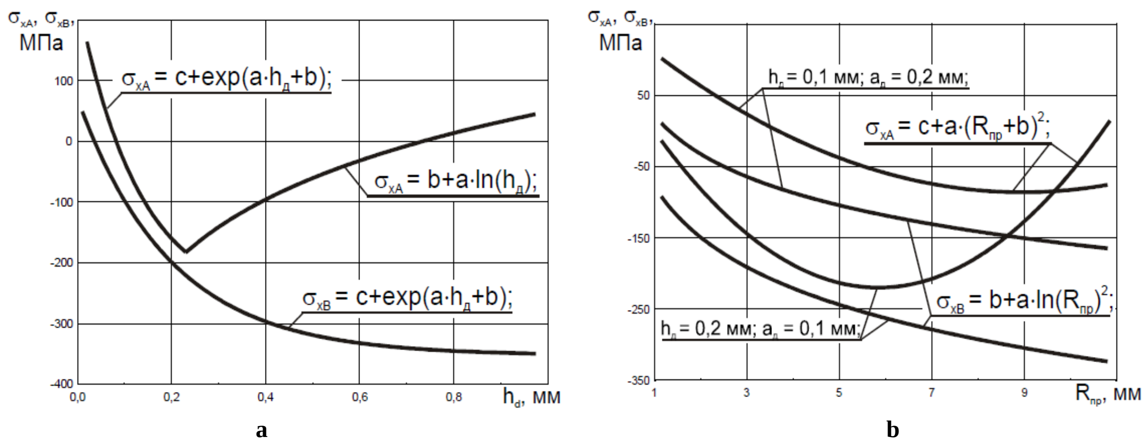
A significant influence on the parameters of the mechanical condition is also exerted by the profile radius R_{pr} and the effective tension of the roller h_d. It was found that Λ and Ψ when changing R_{pr} have extrema, the position of which is determined by the value of the effective gap (Fig. 1, a). When the effective tension increases, the values of the deformation parameters continuously increase (Fig. 1, b).



a **b**

Fig. 1. Interrelationships of the accumulated parameters of the mechanical state: a - with profile radius of the roller; b - with real tension

In order to identify the relationships between the residual stresses and the parameters of the mode, a description of the graphs of the OH components in the categories of the coordinates of the characteristic points was carried out. As an example, graphical dependencies for the axial component of residual stresses are considered below (Fig. 2, a, b). It was established that the largest axial compressive stresses on the surface are observed at significant actual tension of about 0.25 mm [10, 11]. Their further decrease with increasing tension is caused by significantly increasing thermal discharge, while the axial compressive stresses in the first extremum continue to increase (Fig. 2, a).



a **b**

Fig. 2. Interrelationships of axial residual stresses on surface and in the first extremum: a - with real tension; b - with the profile radius of the roller

It was established that for each value of the effective tension, there is a value of the profile radius of the roller at which the compressive stresses on the surface of the part are maximum (Fig. 2, b). The maximum values of the axial compressive stresses at the point of the first extremum increase with the increase of both factors and reach values of 400 MPa [12]. The growth of these factors also increases the actual depth of the location of the extremum from the surface of the part. At the maximum values of the effective tension and profile radius of the roller, it reaches values of 6-8 mm.

The conducted experimental studies made it possible to reveal the relationships between the cyclic durability of N_{CD} and the depth of fatigue crack initiation htr with the parameters of the mechanical state of the PS metal and technological factors in the processing of DSR. It was established that the main parameters of the DSR regime have a hereditary influence on the degree of shear deformation accumulated at the stage of cyclic durability $\Delta\Lambda_{ЦД}$, the largest value of which is observed at $h_д$ = 0.6 mm. As the effective gap increases, the value of $\Delta\Lambda_{ЦД}$ decreases, which is caused by a significant increase in the degree of shear deformation accumulated during DSR.

An increase in the effective gap leads to a decrease in the fatigue crack nucleation depth and the exit of the probable fracture point to the surface [13]. This corresponds to the well-known idea that with a further increase in a, there is an accumulation of limit deformations and destruction of the metal surface at the top of the plastic wave already during mechanical processing. An increase in $R_{пр}$ leads to an increase in the crack nucleation depth, while the highest value of $h_{тр}$ is observed at h = 0.6 mm. When $\Delta\Lambda_{ЦД}$ increases, the crack initiation depth increases.

The analysis showed that the maximum cyclic durability was obtained in such modes of DSR, when residual stresses, depth and degree of strengthening did not reach their maximum values.

Conclusions

For the practical use and implementation of the results obtained in the work, an algorithm for calculating the parameters of DSR processing has been developed, which allows:

1. Determine the quality parameters, integral parameters of the mechanical state (Λ, Ψ, $[T\sigma_{ост}]$) and cyclic durability of the part, taking into account the phenomenon of technological inheritance, based on the given value of the mode parameters.

2. According to the given value of the parameters of the quality and durability of the part under conditions of application of fatigue loads, determine the optimal processing modes.

The program "Calculation of the inherited parameters of the dimensional combined running-in process" is intended for the automated calculation of the accumulation of deformation, the exhaustion of the plasticity reserve and the residual stress tensor and the appointment of rational processing modes that provide the best surface properties. It allows you to calculate DSR parameters in three ways:

The 1st method is practical: calculation based on the experimentally obtained geometric profile of the deformation center, which can be obtained with the help of the program "Processing of profilograms of deformation foci during dimensionally shifted rolling and surface plastic deformation".

The 2nd method is analytical: the starting points are the technological parameters set on the machine during the processing of the part by the DSR method.

The 3rd method is inverse analytical: the initial data are the values of the parameters of the quality of the surface layer, which must be obtained during the processing of DSR, as well as the values of technological factors acting as limitations.

Structural and calculation-analytical models were developed and the physical regularities of the formation of the quality of the surface layer were revealed, taking into account the phenomenon of technological inheritance. It has been found that compared to traditional surface plastic deformation, dimensionally coupled rolling provides higher quality and allows to accumulate more deformation without destroying the surface layer.

An analytical model of the formation of residual stresses has been developed, which is presented in the form of a tensor, which is the sum of the tensor of elastic-plastic stresses, as well as the tensors of elastic and thermal unloading stresses. The nature of the distribution of residual stress components along the depth of the surface layer has been established. The calculations showed that the axial component of the residual stresses, which reaches 400 MPa and the depth of spread of compressive stresses up to 10 mm, is characterized by the greatest stress values.

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Марченко Д.Д., Матвєєва К.С. Дослідження напружено-деформованого стану поверхневого шару при зміцнюючій обробці деталей

У роботі представлені експериментальні дослідження та отримані статистичні моделі впливу режимів обробки на якість поверхневого шару і циклічній довговічності зміцнених деталей машин. Встановлено, що основна впливу на зміцнюючий ефект, вичерпання запасу пластичності металу і формування залишкових напружень надають дійсний зазор різця, дійсний натяг і профільний радіус ролика. Результати показали, що розмірне поєднане обкатування забезпечує високу циклічну довговічність зміцнених деталей в умовах багатоциклового втомного навантаження, що досягає 8 млн. циклів, що в 3,5 рази перевищує довговічність не зміценої деталі і в 1,5 рази - довговічність деталі, зміценої поверхневим пластичним деформуванням. Дослідження показали, що найбільша циклічна довговічність деталі забезпечується при мінімальних значеннях дійсного зазору різця, максимальних значеннях профільного радіусу і значенні дійсного натягу ролика 0,6 мм, що відповідає ступеню вичерпання запасу пластичності обробкою розмірним сумісним обкатуванням $\Psi \approx 0{,}65$. На основі результатів теоретичних і експериментальних досліджень розроблено методику та алгоритм проектування технології обробки розмірним поєднаним обкатуванням. Розроблено програму для ЕОМ, що дозволяє розрахунковим шляхом визначати якість поверхневого шару і циклічну довговічності деталі, виходячи із заданих режимів, а також призначати раціональні режими обробки, що забезпечують задану якість поверхневого шару і циклічну довговічність. На основі результатів досліджень розроблено технологічний процес зміцнюючої обробки деталей машин комбінованим розмірним обкатуванням, який дозволяє формувати стискаючі залишкові напруження в поверхневому шарі обробленої деталі, а також збільшити продуктивність до 2 разів при збереженні або поліпшенні заданих параметрів якості поверхневого шару обробленої деталі.

Ключові слова: розмірне сумісне обкатування, напружено-деформований стан, зміцнююча обробка, поверхнева пластична деформація, залишкові напруження