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Improving the technology for restoring worn parts based on cold plastic deformation

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Abstract

Technological control scheme for forming worn parts during their restoration by deforming broaching is proposed. Particular attention is paid to the study of the stress-strain state, which provided the conditions for creating the necessary plastic flow of the product material towards the worn areas and made it possible to compensate the wear amount in these areas of the product and provide an allowance for subsequent machining. Taking into account the peculiarities of parts restoration technological process, the relationship between the required circumferential strain of the outer surface and the total tension on the hole is established. The influence of the number of deforming elements that perform the required deformation on the accumulated strain on the inner surface of the part was investigated. This made it possible to establish that the maximum accumulated strain of the inner surface is provided by the maximum number of elements with a minimum tension on the element. On the outer surface, the value of the accumulated strain does not depend on the number of deforming elements, but is determined only by the total tension and the workpiece thickness. Based on the simulation of deforming broaching in a wide range of changes in operating parameters, tool geometry and workpiece thickness, an analytical dependence was obtained to determine the angle that ensures the absence of axial strains when the workpiece is deformed. The necessary broaching modes and tool geometry were determined, which will ensure the required dimensions of the machined or restored part.

Key words: parts restoration, deforming broaching, stress-strain state simulation, forming scheme, machining modes, tool geometry.

Introduction

Currently, it is important to introduce advanced technologies into the industry that save material, fuel and energy, and raw materials. One of these technologies is the technology of worn parts restoration, the prospects of which are due to the use of significant resources in their production, which can reach up to 30% of labor and technological equipment in general industrial production [1]. The use of parts restoration technology is an important reserve for increasing the efficiency of modern production. Its economic feasibility is due to the possibility of reusing up to 80% of working parts. The cost of restoring worn parts is significantly lower than the cost of new ones (not exceeding 60%) due to the savings in product material and energy costs for its production [2]. Existing restoration technologies use numerous technological methods that take into account the shape, materials of the worn surfaces and other features of the worn surfaces [3]. For the same part, several variants of restoration technologies can be developed, and then the most effective one can be selected. To make an objective choice of restoration technologies, it is necessary to evaluate the advantages and disadvantages of each technology. One of the most basic requirements when choosing a restoration technology is to ensure that the quality parameters of the restored part are not lower than the new one. In this regard, the use and implementation of waste-free technological processes for restoring the dimensional accuracy of worn parts, especially those whose production is mass or large-scale, is extremely relevant. Such parts include the piston pin. The annual program for its production in the European automotive industry alone is more than 30 million pins. The overall dimensions of the part have the following range: diameter 20-58 mm, length 45-220 mm, its weight varies between 0.2-1.8 kg depending on the engine brand, and, for example, for diesel locomotives and marine diesel engines, the weight of piston pins is quite significant and can reach 4.5 kg [4].

Literature review

Let's consider the existing technologies for restoring piston pins. All pins, regardless of their size, have the same design (Fig. 1) and represent an axisymmetric hollow cylinder with chamfers, which has a wear-resistant outer surface hardened to *HRC* 60-62 and a fairly plastic core [5]. Worn pins can be restored in various ways. The most common of them are: grinding to the repair size, hardening, thermoplastic and electrohydraulic distribution, and electrocontact heating [6].

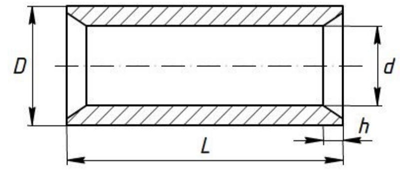


Fig. 1. Typical piston pin design [6]

Grinding the piston pin to a repair size (reducing the outer diameter compared to the nominal diameter) ensures that the worn surface is free of marks, scratches, and macro irregularities. However, the use of such piston pins requires pistons with reduced hole sizes in the bosses. For this reason, the considered method of restoring piston pins is limited in use [7].

The restoration of piston pins by ironing and chromium plating [7], despite its high efficiency and productivity, as well as the ability to build up a metal layer 2-3 mm thick, is not currently widespread. This is due to the low mechanical properties of iron, both in terms of strength and wear resistance, and requires the use of additional thermal operations.

There is also a thermoplastic distribution method [6], which is used to restore worn piston pins. It is realized as follows. Worn piston pins are heated by high-frequency currents above the temperature of pearlite-asthenite transformation. Depending on the cooling technology, the liquid is passed either through the pin hole or by counter or parallel flows through the pin hole and the outer surface with a time shift. This cooling creates a difference in the cooling rates of the inner and outer layers, which, by fixing the volumetric expansion of the metal, ensures an increase in the outer diameter. According to the authors of [6-8], the process of pin distribution simultaneously involves heat treatment of hardening and low tempering. However, it should be noted that the process of hydrothermal distribution causes a heterogeneity of diameter increase along the length of the pin and thus a type of dimensional error such as corsetry occurs. After that, the pins are subjected to five times of grinding and polishing. It should be noted that the unevenness of the machining allowance along the outer diameter of the part leads to uneven and increased metal removal, a decrease in the depth of the cemented layer, and the appearance of areas with reduced hardness and wear resistance. In addition, during thermoplastic distribution, the increase in the outer diameter of the worn pins is due to the presence of internal stresses arising from cooling and the phase transition of austenite to martensite.

According to [9], simultaneously with the distribution of the pin, its heat treatment is carried out – hardening and low tempering. However, in the process of thermoplastic distribution, there are no conditions for low-temperature tempering. Moreover, as studies [8] have shown, the presence of harsh water cooling conditions for alloyed cemented steels of the 12KHN3A type when they are heated above the pearlite-austenite transformation temperatures can lead to cracks in the cemented layer. This is evidenced by Fig. 2, which shows the surface of the piston pin of a D-240 diesel engine restored by hydrothermal distribution, where the appearance of cracks in the cemented layer can be clearly seen.

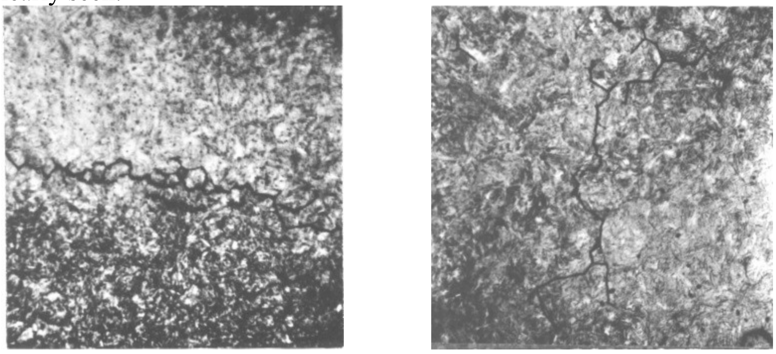


Fig. 2. Microstructure of piston pin cemented layer made of 12KHN3A steel restored by thermoplastic distribution [10]

As proof of low-temperature tempering absence in the process of thermoplastic distribution, and therefore of structures present in the pins restored in this way, which tend to move to a more equilibrium state, the following experiment was conducted by the author [10]. The pin, restored by the thermoplastic distribution method, was annealed in a protective environment. In this case, the outer diameter of the annealed pin decreased by an unacceptable amount (Fig. 3) as a result of internal stress relaxation.

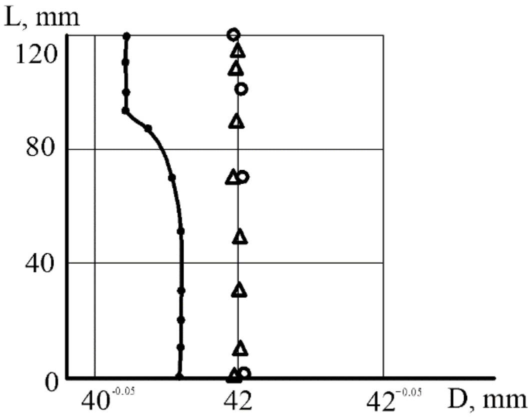


Fig. 3. Changes in the size of the pin generatrix restored by different methods after annealing: ● – after hydrothermal distribution and annealing; Δ – after deforming broaching; ○ – after deforming broaching and annealing [10]

A similar fact can occur during the operation of the pins, since the operating conditions of an internal combustion engine are characterized by the presence of high temperatures and alternating loads. This can cause a reduction in the strictly regulated outer diameter of the pin, which can lead to engine failure.

According to [4], the restoration of piston pins by the method of electrocontact heating and combined spray cooling is more advanced than hydrothermal distribution, but also has a number of disadvantages typical to the methods of restoring parts based on the use of thermal strains. The microstructure of the quenched cemented layer of the restored pins is martensite with the inclusion of cementite, residual austenite, and troostite [7]. This indicates non-compliance with the basic requirements for the technological process of cemented steels heat treatment during heat treatment and leads to the appearance of defective features in the restored pins (the presence of residual austenite).

As follows from the analysis of works [4, 7] related to the dimensional accuracy restoration of worn piston pins by heating and subsequent cooling, they all have common disadvantages. The most significant of them is the lack of allowance on the outer surface of the restored pin for subsequent machining, the presence of areas with reduced hardness and wear resistance, the possible appearance of cracks in the cemented layer, and the mismatch of the restored pin microstructure with technical requirements. All of this leads to a significant percentage of restored products rejects and does not ensure the stability of the operational parameters of the restored piston pin quality. In addition, these methods are energy-intensive, require special equipment and are not environmentally friendly.

At the same time, the use of cold plastic deformation (CPD) methods, as noted in works [11, 12], allows to ensure the required level of products working surface quality parameters.

The undoubted advantages of CPD methods are [11, 12]:

- maintaining material integrity by redistributing the product material to the worn areas;
- improving the physical and mechanical properties of the processed product material;
- the possibility of combining thermal and chemical-thermal operations makes it possible to create hybrid technologies;
- improved technological inheritance makes it possible to maintain the quality parameters of parts, even when using additional finishing operations;
- ensuring that the process does not have a negative impact on the environment;
- the ability to automate the process, which ensures the use of CPD in mass production.

According to a number of works [13-15], the development of a technology for the restoration of worn parts should be based on the study of the stress-strain state (SSS). This will provide the conditions for creating the necessary plastic flow of the product material towards the worn areas, which will compensate for the amount of wear in these areas of the product and provide allowance for subsequent machining.

The Institute of Superhard Materials of the National Academy of Sciences of Ukraine created a highly efficient technological process for restoring piston pins based on deforming broaching [8, 16], which made it possible to solve the problems of ensuring the dimensional accuracy of the pin's outer surface, as well as to develop a new scheme for deforming the pin with a change in the bearing face [17]. Based on this scheme, the installation design for pin distribution in mass and large-scale production was developed. The pins restored by deforming broaching do not have the same disadvantages as the pins restored by thermoplastic distribution (Fig. 3). Regarding the choice of the forming scheme, the authors of [8, 16] conducted experimental studies on the basis of which the required geometric parameter of the tool was selected. However, the absence of a definite relationship between the strain of the pin hole and the strain of its outer surface will not allow optimizing the workpiece forming scheme by selecting the necessary broaching modes and tool geometry.

Purpose

The aim of the work is to develop a methodology for technological control of worn parts shape formation during their restoration by deforming broaching. Achieving this goal requires solving the following tasks:

– to develop a methodology and study the SSS in the deformation zone during deforming broaching and its influence on the change in processed workpiece dimensions;

– to establish the relationship of operating parameters and tool geometry to changes in processed workpiece dimensions;

– to develop a methodology for technological control of workpiece forming, with the help of which to determine the necessary modes of broaching and tool geometry, which ensure the required processed part dimensions.

Research Methodology

To analyze the SSS of the workpiece material and study the change in machined part dimensions, a finite element model (FEM-Model) of the deforming broaching process (DBR) was developed according to the following scheme (Fig. 4). The SSS simulation of an axisymmetric workpiece made of plastic material during deforming broaching was carried out using the DEFORM 2D/3D^{TM}V 11.0 software package [18].

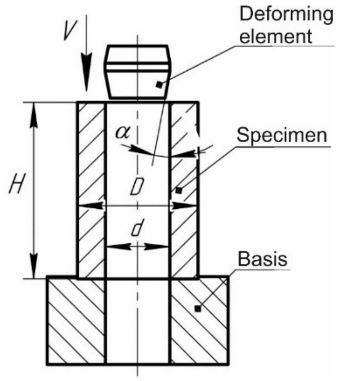
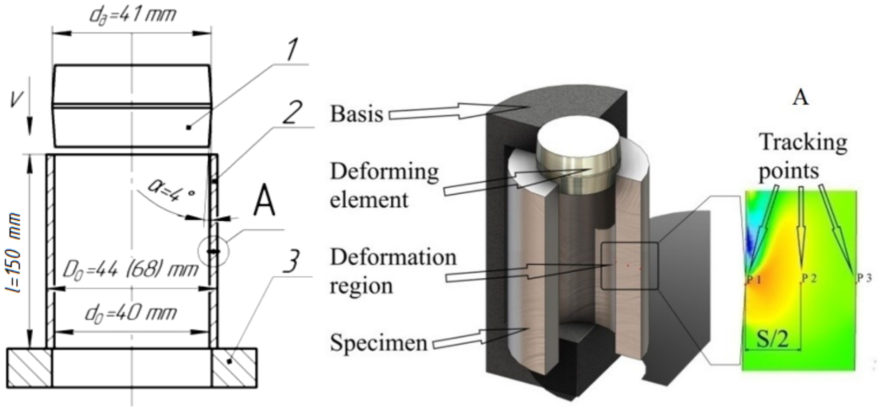


Fig. 4. Scheme of deforming broaching

To analyze the influence of the tool's geometric parameters on the characteristics of the SSS and the workpiece's geometric dimensions, the angle of the working cone inclination of the deforming element *α* was changed and amounted to 2°, 4°, and 8°, respectively.

Taking into account the above conditions, a finite element model of the considered process was built (Fig. 5).



a) b)

Fig. 5. FEM model construction: a) workpiece with dimensions: 1 – deforming element; 2 – the studied axisymmetric workpiece; 3 – base; b) model scheme

The simulation process considered the machining of two workpieces with the same internal diameter. The inner diameter of the workpieces is d_0 = 40 mm, the outer diameter of the first workpiece is D_{01} = 44 mm, the second is $D_{02} = 68$ mm, and the length is $l = 150$ mm. The deforming element is made with the angle of the working and return cone $\alpha = 4°$. The diameter of the working element is equal to $d_e = 41$ mm, i.e., a nominal tension of 1 mm is created during its passage. The movement speed of the deforming element is $V = 0.5$ mm/s.

As the material for the study, we chose 12KHN3A steel, the chemical composition and mechanical properties of which are presented in Table 1. The DEFORM material library [18] contains an analog of the above material, DIN 14NiCr14, which has similar mechanical characteristics. It was used in the simulation of the SSS. In the DEFORM software, the flow curve for this material is defined by points (Table 2). The analysis of SSS was carried out in the middle of the length of the workpiece at three points (Fig. 5, b).

Table 1

Chemical composition and mechanical properties of 12KHN3A steel [19]

Chemical composition, %					Mechanical properties			
C	Mn	Si	Cr	Ni	*HB* hardness, MPa	Tensile strength σ_B, MPa	Poisson's ratio, μ	Elastic modulus, $E \cdot 10^5$, MPa
0.09-0.16	0.3-0.6	0.17-0.37	0.6-0.9	2.75-3.15	220 – 230	930	0.28	2

Table 2

Flow curve points of 14NiCr14 steel

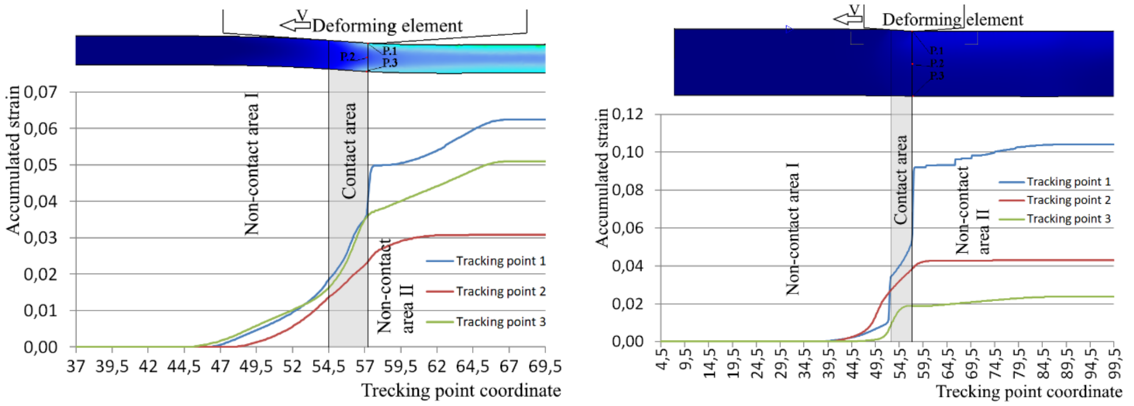
e_i	0	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.85
σ_i	356.8	506.4	648.8	780.8	824.6	835.6	835.0	830.2	825.4	818.4	814.5

At each point, the strain intensity e_i, hydrostatic pressure σ_0, stiffness coefficient of the stress state, axial stress σ_z, axial strain e_z, and circumferential strain e_φ were determined.

The obtained FEM-model of the process was used to study the SSS of each of the deformation zone areas in the DBR simulation of a workpiece made of plastic material.

Results

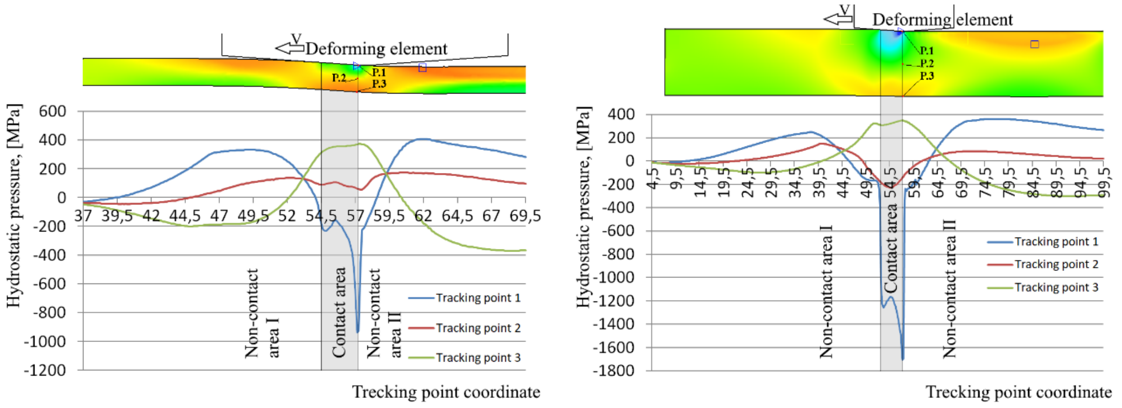
Let us consider the results of the simulation. Fig. 6 shows the change in the accumulated strain during the simulation of the deformation process of thin-walled and thick-walled workpieces.



a) b)

Fig. 6. Variation of the parameter ei in the deformation zone when simulating the deformation process of 12KHN3A steel workpieces by a deforming element with tension $a/d_0 = 0.025$ and thickness $t_0/d_0 = 0.025$: a) 0.05; b) 0.35

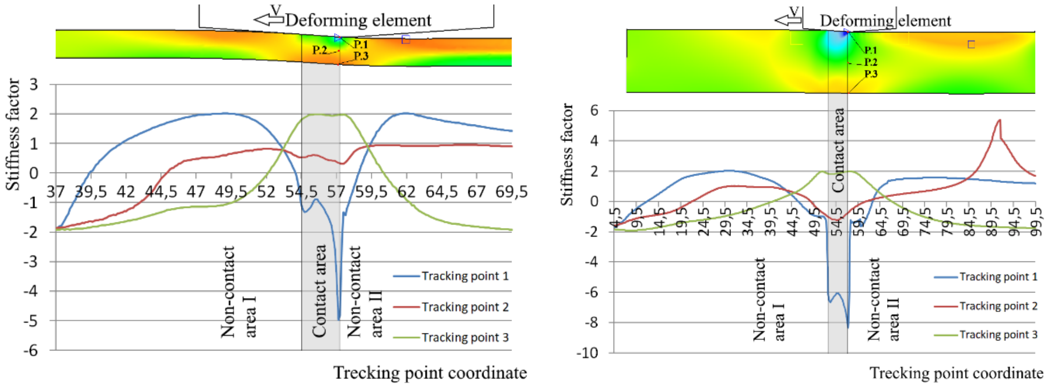
Fig. 6 shows that strain accumulation begins in noncontact zone I, then the main part of the deformation occurs in contact zone II, and in noncontact zone III, the deformation in the deformation zone is completed. It should be noted that the values of the accumulated strain in noncontact zones I and III are approximately equal to each other. Comparing Fig. 6 *a* and *b*, it follows that the changes in the accumulated strain for thin-walled and thick-walled workpieces are similar, but there are differences. In both cases, the value of the maximum accumulated strain corresponds to the inner surface of the workpiece. It decreases as the workpiece radius increases. But thin-walled workpieces have their own peculiarities. On the outer surface (Tracking point 3), the accumulated strain is greater than on the middle surface (Tracking point 2). This is not the case for thicker-walled workpieces. There, the strain gradually decreases with increasing thickness and its minimum value corresponds to the outer surface (Tracking point 3). This can be explained by the following. In a thin-walled workpiece, the strain along the wall thickness is almost through and uniform. The hydrostatic pressure (Fig. 7) for thin-walled workpieces varies from –1000 MPa in the contact zone to a value of 400 MPa, and for thick-walled workpieces from –1600 MPa to 400 MPa.



a) b)

Fig. 7. Changes in hydrostatic pressure σ_0 in the deformation zone when simulating the deformation process of 12KHN3A steel workpieces by a deforming element with tension $a/d_0 = 0.025$ and thickness $t_0/d_0 = 0.025$: a) 0.05; b) 0.35

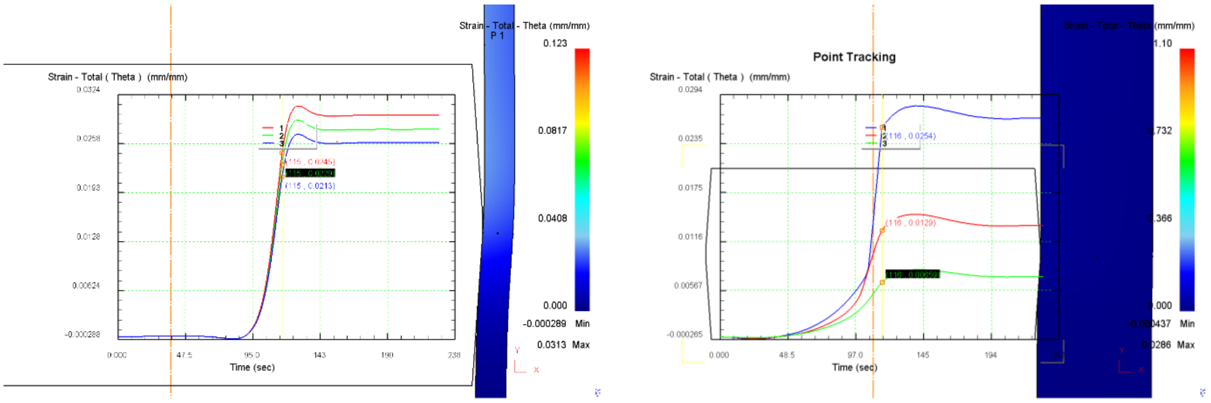
The stress state coefficient in both cases (Fig. 8) is $\eta = +2$ on the outer surface corresponding to the contact zone, and $\eta = -5$ (Fig. 8, a) and $\eta = -8$ (Fig. 8, b) on the inner surface where the maximum strain occurs.



a) b)

Fig. 8. Changes in the value of the stress state coefficient η in the deformation zone when simulating the deformation process of 12KHN3A steel workpieces by a deforming element with tension $a/d_0 = 0.025$ and thickness $t_0/d_0 = 0.025$: a) 0.05; b) 0.35

For thick-walled parts, the hydrostatic pressure at the middle surface (Tracking point 2) is zero, the stress value is also close to zero, and the accumulated strain is greater than Tracking point 3. At the same time, the thin-walled workpiece has a positive value of hydrostatic pressure at points 2 and 3, and at point 3 it is greater and causes the appearance of a stress state close to biaxial tension, as evidenced by the value of the stress state coefficient $\eta = +2$.



a) b)

Fig. 9. Changes in the value of the circumferential component of the strain tensor e_φ in the deformation zone when simulating the deformation process of 12KHN3A steel workpieces by a deforming element with tension $a/d_0 = 0.025$ and thickness $t_0/d_0 = 0.025$: a) 0.05; б) 0.35

Consider a change in the circumferential component of the strain tensor, which determines the increase in the outer diameter of the workpiece. In Fig. 9 shows the results of simulating the deformation of thin-walled and thick-walled workpieces.

The nature of the change in this parameter does not depend on the thickness of the workpiece, although the difference between the e_φ values for Tracking point 1, 2, 3 is insignificant for thin-walled workpieces, indicating a through homogeneous strain in this case (Fig. 9, *a*). For thick-walled ones, this difference is significant. The maximum value corresponds to the inner surface of the workpiece, and the minimum value to the outer surface (Fig. 9, *b*). The maximum value of the circumferential strain occurs in the contact zone. In non-contact zones, the value of e_φ is insignificant.

The influence of technological factors and tool geometry on the circumferential strain on the outer surface is characterized by Fig. 10.

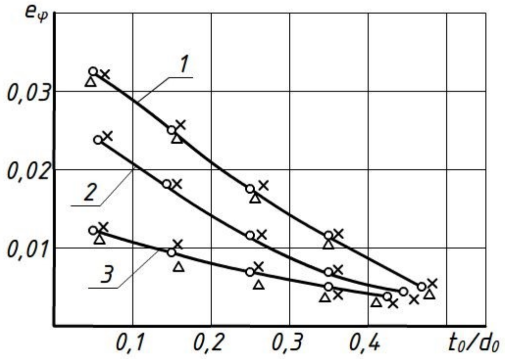


Fig. 10. Dependence of the circumferential strain e_φ on the thickness of the workpiece t_0/d_0 when simulating the workpiece strain with tension on the element a/d_0: 1 – 0.0375; 2 – 0.025; 3 – 0.0125 with different angles α: ○ – 4°; × – 8°; Δ – 2°

As can be seen from Fig. 10, the circumferential strain of the outer surface practically does not depend on the angle α, but is determined only by the thickness of the workpiece and the tension on the element. The approximation of the data shown in Fig. 10, made it possible to obtain a dependence by which it is possible to determine the required tension depending on the required circumferential strain:

$$e_\varphi = 0{,}95a/d_0 - (1{,}95a/d_0)t_0/d_0. \tag{1}$$

The required total strain of the inner surface is determined by the equation:

$$\Sigma a/d_0 = \frac{e_\varphi^*}{0{,}95 - 1{,}95t_0/d_0}. \tag{2}$$

When designing a workpiece restoration process, the circumferential strain required to compensate for wear and provide allowance for subsequent machining is determined. Then, according to dependence (1), the required total tension is determined to ensure that this circumferential strain is obtained for a specific workpiece thickness. If there is a need to perform several deformation cycles, the total tension is divided into several transitions, whereby:

$$\Sigma a/d_0 = a_1/d_0 + a_2/d_0. \tag{3}$$

Studies [11] have shown that assessing the plasticity utilization rate is important when plastic strain is followed by thermal or chemical-thermal treatment. In this case, the properties of the prestrengthened material largely depend on the plasticity reserve utilization rate accumulated during previous operations. The authors of works [10, 11] recommend limiting the value of the used plasticity resource within the limits:

$$\psi_{\max} \le [\psi]^*, \tag{4}$$

where $[\psi]^* = (0{,}25 \div 0{,}3)[\psi]$, $[\psi]$ – maximum deformation of the workpiece corresponding to a specific stress state coefficient.

After determining the required strain of the outer surface and the corresponding total hole tension, the workpiece must be checked for the remaining plasticity on the outer and inner surfaces of the workpiece.

Consider how the number of deforming elements that perform the required total strain of the hole affects its strain intensity. Let us consider three cases in which the same total strain $\sum a/d_0 = 0.075$ is performed. In the first case, the strain is performed by 6 deforming elements with a tension on the element $a/d_0 = 0.0125$. In the second case, it is performed by 3 deforming elements with a tension on the element $a/d_0 = 0.025$. And in the third case, it is performed by 2 deforming elements with a tension on the element $a/d_0 = 0.0375$. As follows from Fig. 11, the maximum accumulated strain $e_0 = 0.76$ occurs when deformed by 6 deforming elements. A smaller strain $e_0 = 0.27$ is observed when the total tension is applied by 3 deforming elements. And the smallest strain on the inner surface of the hole $e_0 = 0.18$ is observed when deformed by 2 elements.

At the same time, no such significant difference in the values of the accumulated strain from the number of deforming elements is observed on the outer surface. The number of deforming elements practically does not affect its value and on the outer surface of the part is in all three cases $e_0 = 0.06$, 0.07, 0.072, respectively.

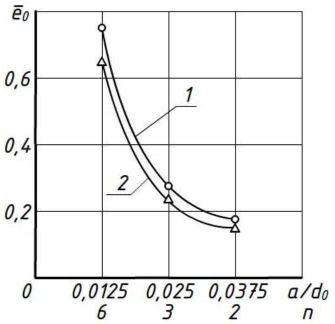
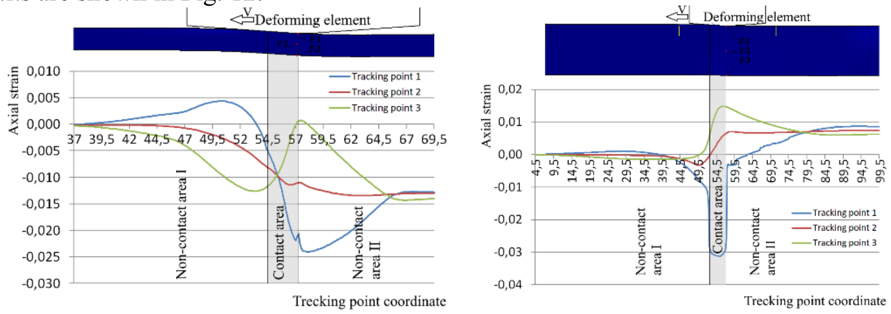


Fig. 11. Dependence of the accumulated strain on the inner surface of a 12KHN3A steel workpiece during simulation of its strain by working elements with an angle of α = 4° on the tension on the element and the number of deforming elements that perform the total strain, workpiece thickness t_0/d_0: 1 – 0.35; 2 – 0.2

The change in the accumulated strain at the thick-walled state $t_0/d_0 = 0.2$ has a similar character, i.e., the wall thickness has practically no effect on the nature of the change in the accumulated strain depending on the number of broached elements. Therefore, taking into account the significant effect of the number of deforming elements on the value of the accumulated strain on the inner surface of the part, we check the used plasticity resource on the deformed hole surface.

After determining the number of elements and the tension on them according to dependence (3), we select the deformation scheme. It can be compression, tensile, or schemes with a change in the supporting face [17].

Further, according to the thickness of the workpiece and the tension on the element determined by dependence (1), which provides the required increase in the outer diameter of the workpiece, we determine the angle α, which will provide the required axial deformation of the workpiece. As is known from scientific works [11, 12] on determining the workpiece strain, deforming broaching causes shortening of parts, i.e., during the dispensing of the inner hole, the outer diameter of the workpiece increases and its length decreases. However, some works [20, 21] note that in addition to shortening the workpiece, it can be lengthened, which can be used to restore the worn axial dimension of the part. Therefore, we considered the possibility of changing the axial strains of the workpiece. To do this, we simulated the deformation process of a 12KHN3A steel workpiece to determine its axial dimensions in a wide range of changes in the part thickness, element tension, and angle α. Examples of simulation results are shown in Fig. 12.



a) b)

Fig. 12. Variation of the axial component of the strain tensor e_z in the deformation zone when simulating the deformation process of 12KHN3A steel workpieces by a deforming element with tension a/d_0 = 0.025 and thickness t_0/d_0 = 0.025: a) 0.05; b) 0.35

Fig. 12 shows that when thin-walled parts are deformed (Fig. 12, *a*), the workpiece is shortened. At the same time, when thick-walled parts are deformed, the workpiece is elongated. If there is shortening and lengthening, then there should be a zero change in the axial dimension of the workpiece. The simulation results, which indicate the presence of a zero size of the machined workpiece depending on its thickness and tension on the element, are shown in Fig. 13.

The approximation of the data shown in Fig. 13, allowed us to obtain an analytical dependence for determining the angle α, which ensures the absence of axial strains depending on the thickness of the workpiece and the tension on the element:

$$\alpha^* = \frac{0,35\left(1+100a/d_0\right)}{t_0/d_0}. \tag{5}$$

The process of controlling the forming for a given workpiece thickness is as follows. First, the circumferential deformation required to compensate for wear and provide an allowance for further processing is determined. Then, according to the dependence (1) obtained as a result of simulation, the required total tension on the element ∑a is determined according to dependence (2).

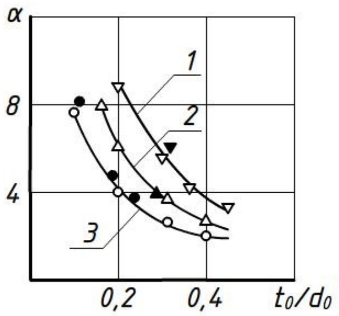


Fig. 13. The dependence of the angle α, which ensures the absence of axial strains on the thickness of the workpiece, was obtained by simulating the deformation process of a 12KHN3A steel workpiece with different tensions: 1 – 0.0375; 2 – 0.025; 3 – 0.0125; ●, ▲, ▼ – used experimentally obtained data [16]

If the part is subjected to thermal or chemical-thermal operations during processing, it is mandatory to check the used plasticity resource on the restored surface of the part.

Then, based on a given thickness and a certain tension, which is responsible for obtaining the required outer diameter size, we determine the angle α, which ensures a zero change in the length of the workpiece. This is done according to the previously obtained experimental dependence (5) obtained from the simulation results.

Subsequently, depending on the requirements for the workpiece, we fulfill the conditions under which the workpiece either elongates $\alpha > \alpha^*$, shortens $\alpha < \alpha^*$, or its axial dimension remains unchanged $\alpha = \alpha^*$.

The conducted studies made it possible to build an algorithm for technological control of workpiece forming (Fig. 14).

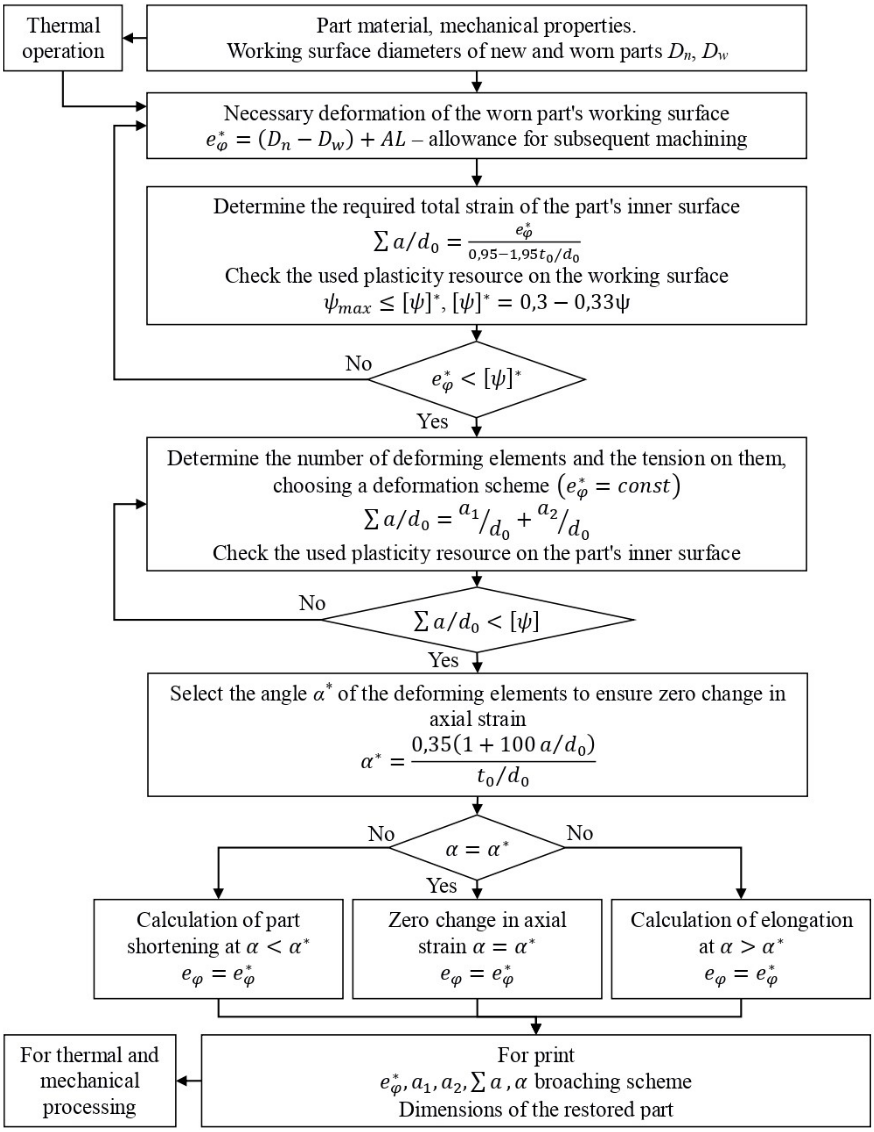


Fig. 14. Algorithm scheme of the technological process for restoration or processing using plastic strain of a hollow axisymmetric part

The developed scheme of the algorithm for constructing a technological process for restoring a hollow axisymmetric part using plastic strain has been successfully tested during the design of such technological processes for restoring worn parts:

– worn piston pins of 10D100 diesel locomotive engines at the Dnipro Locomotive Repair Plant. During the restoration of 10D100 piston pins, the recommendations presented in the forming scheme (Fig. 14) provided a zero change in length, i.e., the length of the pin did not change after increasing the outer diameter. The dimensions of the 10D100 pins are $t_0/d_0 = 0.4$, the length of the pin is 182 mm, the outer diameter of the pin is 80 mm, and the weight of the pin is 4.5 kg. Material of the pins – 12KHN3A steel;

– restoration of the dimensions L and D_1 geometric accuracy of the cardan joint worn crosspieces (Fig. 15) [20] at the Institute of Superhard Materials of the National Academy of Sciences of Ukraine. During their strain, there is a simultaneous increase in the outer diameter and an increase in the original axial dimension h to h_1, which made it possible to finishing the worn faces to the required size.

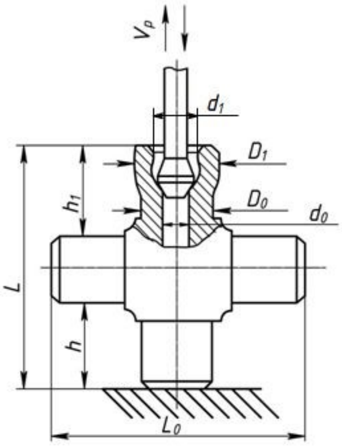


Fig. 15. Scheme of a worn crosspiece deformation [20]

Conclusions

Controlling the parts forming scheme is an important aspect of developing a technological process for restoring worn parts and machining new parts using CPD. This allows to obtain the required dimensions of the parts after their deformation. When machining new parts, the required allowances for subsequent machining are obtained, and when restoring worn parts, the dimensions of the worn surface are obtained to compensate wear and provide allowances for subsequent machining.

The conducted studies allowed us to draw the following conclusions:

– developed methodology for studying the SSS by simulating the deformation process of workpieces with different thicknesses in a wide range of changes in the broaching modes and tool geometry using the DEFORM 2D/3D^{TM}V 11.0 software package;

– based on the study of SSS, the relationship between the required circumferential strain of the outer surface e_φ and the total tension on the hole is established. It is shown that the parameter e_φ does not depend on the angle α, but is determined by the thickness of the workpiece and the total tension. The dependence for determining the required tension, which ensures the desired value of the parameter e_φ, is obtained;

– the influence of the number of deforming elements that perform the required circumferential strain on the accumulated strain on the inner surface of the part is determined. It is shown that the maximum accumulated strain of the inner surface is provided by the maximum number of elements with minimal tension on the element. On the outer surface, the value of the accumulated strain does not depend on the number of deforming elements, but is determined only by the total tension and thickness of the workpiece;

– the necessity of checking the obtained dimensions of the part after plastic strain by the parameter of the used plasticity is proved;

– it is shown that after obtaining the required value of the circumferential strain, it is necessary to determine the angle α, which will ensure a zero change in its axial strain. Based on the process of simulating strain in a wide range of changes in operating parameters, tool geometry, and workpiece thickness, an analytical dependence is obtained for determining the angle α, which ensures the absence of axial strains during workpiece deformation. To obtain the required axial dimensions of the processed workpiece, we choose an angle α from the following conditions: to obtain a zero change in length – angle $\alpha = \alpha^*$, to obtain a shortening $\alpha < \alpha^*$, to obtain an elongation $\alpha > \alpha^*$;

– an algorithm for technological control of the hollow axisymmetric part forming was developed, which allowed determining the necessary broaching modes and tool geometry to ensure the required dimensions of the machined or restored part.

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Удосконалення технології відновлення зношених деталей на основі холодного пластичного деформування

Запропоновано схема технологічного управління формоутворенням зношених деталей при їх відновленні деформуючим протягуванням. Особливу увагу приділено дослідженню напружено-деформованого стану, що забезпечило умови для створення необхідної пластичної течії матеріалу виробу по направленню до зношених ділянок та дозволило компенсувати величину зносу на цих ділянках виробу та забезпечити припуск під наступну механічну обробку. З врахуванням особливостей технологічного процесу відновлення деталей встановлено зв'язок необхідної окружної деформації зовнішньої поверхні з сумарним натягом на отвір. Досліджено вплив кількості деформуючих елементів, які виконують необхідну деформацію, на накопичену деформацію на внутрішній поверхні деталі. Це дозволило встановити, що максимум накопиченої деформації внутрішньої поверхні забезпечується максимальним числом елементів з мінімальним натягом на елемент. На зовнішній поверхні значення накопиченої деформації не залежить від кількості деформуючих елементів, а визначається тільки сумарним натягом і товстостінністю заготовки. На основі симуляції деформуючого протягування в широкому діапазоні зміни режимних параметрів, геометрії інструменту та товстостінності заготовки отримана аналітична залежність для визначення кута, який забезпечує відсутність осьових деформацій при деформуванні заготовки. Визначенні необхідні режими протягування і геометрію інструменту, які забезпечать отримання необхідних розмірів обробленої або відновленої деталі.

Ключові слова: відновлення деталей, деформуюче протягування, моделювання напружено-деформованого стану, схема формоутворення, режими обробки, геометрія інструменту.