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Evaluation of optimal grain hardening modes to increase fatigue resistance of parts made of high-strength steels

Georgy Kravchenko[1], *Konstantin* Kravchenko[1] *Andrey* Smolyaninov[2*], and *Svetlana* Lapteva[3]

[1]Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, 125993 Moscow, Russia
[2]Voronezh State Technical University, 84, 20-letiya Oktyabrya str., 394006 Voronezh, Russia
[3]Moscow State University of Civil Engineering, 26, Yaroslavskoe shosse, 129337 Moscow, Russia

Abstract. Recommendations on the choice of optimal modes of shot blasting hardening of steel 30HGSN2A (30ХГСН2А) according to the criterion of cyclic durability are given. On the basis of experimental studies of the influence of technological parameters and properties of the surface layer, a generalized technological parameter was proposed, including the values of the diameter of the shot and its velocity at 98% coverage of the surface of the part with 4-6 times fraction prints.

1 Introduction

In the branches of mechanical engineering, various technological methods are widely used to ensure high fatigue strength of power, high-load structural elements. Among which, especially common, as very effective and universal, methods of surface plastic deformation and, especially, varieties of technological processes of shot blast processing. The basis of these methods is the plastic deformation of the thin surface layer of the material of the part under the blows of the shot [1]. There are several technological methods depending on the mechanism of communication of the kinetic energy fraction. In the aviation industry, the following methods are most common: shot blasting, shot blasting, vibration and shock-drum. These methods are practically the only ones in the hardening of large-sized, high-load aircraft parts that have a complex and shaped surface with the presence of various forms of voltage concentrators (power frames, spars, monolithic panels, power elements of the chassis and hydraulic systems, airframe mounting units and many others).

2 Model and method

Of the above technological methods, the most promising in increasing the fatigue resistance of power parts operating in severe conditions of variable loading are shot blasting processes, jet-mechanical and jet-pneumatic action. These methods have high productivity (20-30 m^2/h)

* Corresponding author: u00781@vgasu.vrn.ru

and versatility, and also allow you to change the processing modes in the process of hardening various parts of the parts.

The main technological parameters of shot blasting hardening are: the diameter of the shot D, the rate of its collision with the surface of the part v, the hardening time of the unit surface t. Other technological parameters of shot blast hardening include the material of the shot and its shape, the specific flux density of the shot; the distance from the nozzle cut to the surface to be treated; the angle of collision of the shot with the surface and other parameters related to the features of a particular technological equipment, the route and the relative movement of the part and nozzle of the installation [2].

When designing the technological process of shot blast hardening, it is very important to choose such technological parameters and modes that will ensure the maximum increase in the required performance properties of the machined parts. When strengthening the power parts of aircraft structures, first of all, it is necessary to achieve an increase in the characteristics of fatigue resistance. It is also possible to increase wear resistance, corrosion resistance, fretting corrosion and some other performance characteristics. The increase in these properties is associated with the formation in the process of plastic deformation by the fraction of new properties and the stress-strain state of the surface layer by the material of the part [3]. This is, first of all, an increase in its mechanical characteristics (tensile strength and hardness), the appearance of favorable surface residual stresses, a change in the micro-relief of the surface, a change in the fine structure, phase composition, the level of local microvoltages, etc.

The role or contribution of each of these properties of the surface layer in improving the performance characteristics varies significantly depending on a number of factors, such as the mechanical properties of the material of the part, its geometry in the places of hardening (the presence of structural stress concentrators), the type, level and frequency of external variable loading, external conditions and operating temperature, the need for possible restoration during operation, etc. For example, in the hardening of high-strength steels and alloys operating at normal temperatures and under conditions of multicyclic fatigue, the main role in increasing the endurance limit is given to compressive residual stresses, as well as the thickness of the hardened layer (the depth of the rivet), and to a lesser extent the size of the rivet itself and the roughness of the surface [4,5]. For the same materials, but working in the field of multicyclic fatigue, in which local plastic deformation may appear in local places, leading to relaxation of residual compressive stresses, the role of rivet and roughness increases. In the hardening of parts made of light alloys, the main role is given to the degree of riveting, the size and depth of the residual compressive stresses and the parameters of roughness. Moreover, the degree of influence of each of these parameters of the surface layer varies from the level of external variable loading [6]. For parts made of heat-resistant steels, the role of residual stresses is very small, because at high temperatures their intense relaxation occurs and they can completely disappear.

3 Research and results

As illustrations in Fig. 1 shows the joint and separate influence of the values of residual compressive stresses of the σ_{rem} and the microhardness of the surface layer HV on the hanging of the endurance limit of the part σ_{-1} depending on the hardness of the HRC (strength) of the material of the part.

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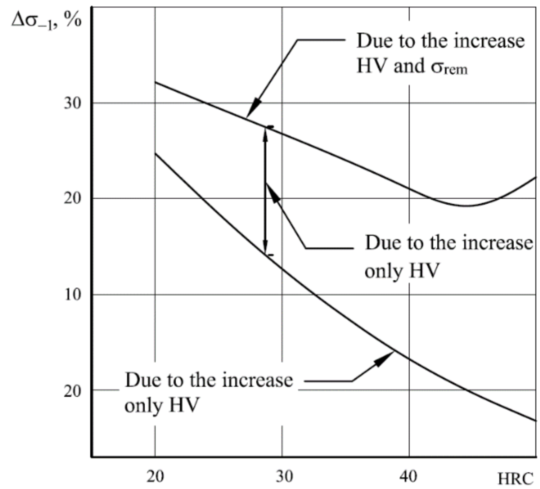

Fig. 1. Diagram of the influence of the properties of the hardened surface layer σ_{rem} and HV, depending on the strength (hardness) of the material of the part on increasing the endurance limit σ_{-1}.

Therefore, when choosing the technological parameters of shot shock hardening of parts in order to increase their fatigue resistance, it is necessary to take into account which class (by purpose, geometry, dimensions, etc.) these parts, their material and operating conditions (AC voltage level and operating temperature) belong. It is necessary to prescribe such treatment modes that form new parameters of the quality of the surface layer and allow to obtain the required (maximum) increase in the characteristics of fatigue resistance, taking into account all influencing factors. In fig. 2 shows a general scheme for taking into account the main factors in the development of highly efficient processes of surface plastic deformation in the process of production of parts and in the process of operation when restoring their resource [7, 8].

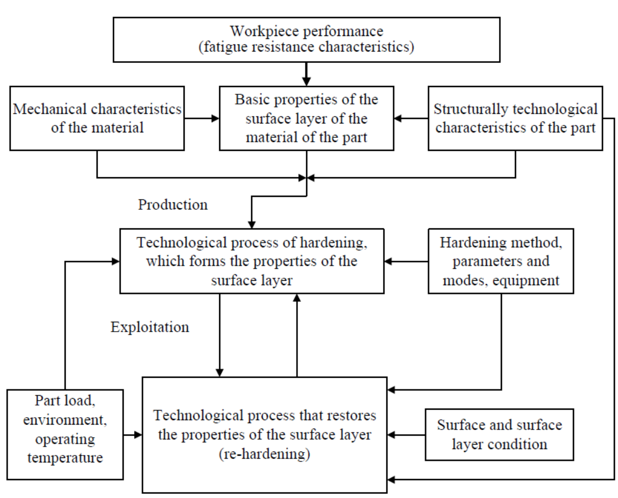

Fig. 2. Scheme of consideration of the main factors in the development of hardening technology by methods of surface plastic deformation.

In production, when assigning hardening modes, typical technological processes, production instructions and technological recommendations are usually used, which, as a rule, take into account the features and specifics of the equipment used. These process documents are developed on the basis of experimental studies carried out on samples or models of parts and joints, which, after hardening in various modes, test fatigue strength. These studies, as a rule, are carried out in industry laboratories and research institutes.

In the instructions developed at All-Russian Research Institute of Aviation Materials and Institute of Aviation Technology, the aviation industry recommends the use of the size of the shot and its speed in a fairly wide range, depending on the type of equipment used, the material of the hardened part and the geometry of the local hardening points. Since in most industrial equipment the shot is accelerated in the stream of compressed air, and in part of the equipment - by a rotating impeller shot blast wheel, the instructions give the recommended values of compressed air pressure P or speed of rotation of the shot blast wheel N. To estimate the actual flight speed and impact of the V shot with the surface, there are special training schedules and tables obtained experimentally for each specific type of equipment and establishing the relationships v = f(P, D) or v = f(N, D). So when strengthening aircraft parts from structural alloys for one equipment, a shot diameter of 2... 3 mm and air pressure 0,3... 0.5 MPa, and for other equipment the diameter of the shot is 0.3... 1.2 mm at an air pressure of 0.4... 0.5 MPa. The instructions also provide other technological parameters of hardening inherent in a particular type of equipment. The hardening time of a unit of surface, according to All-Russian Research Institute of Aviation Materials instructions, shall be determined on the basis of ensuring that the density of the surface with shot prints is not less than 90% [9].

When choosing the size, material, and flight speed of the shot, one should take into account the geometry of the local hardening sites of the parts, the mechanical characteristics of its material, the initial surface roughness and the required micro-relief after hardening, as well as the requirements of the corrosion resistance of the surface layer. The transition to the use of smaller shots and microbeads and to lower speeds (air pressures) allows you to increase the accuracy and frequency of the workpiece, as well as reduce the warping of thin-walled structures, as a rule, while maintaining efficiency in increasing fatigue strength. It should be noted that a decrease in the diameter of the shot does not lead to a noticeable decrease in the maximum value of compressive residual stresses, but leads to a decrease in the depth of their propagation and to a decrease in the thickness of the plastically deformed surface layer [10].

A large number of works are devoted to the study of the effectiveness of shot blasting hardening depending on the technological parameters of processing and taking into account the influence of numerous factors. In almost all, there is a clear trend: with an increase in the size of the shot and its speed, the fatigue resistance of the part initially increases, and then decreases. That is, there is a pronounced extremum corresponding to a certain combination of values D and v. In Fig. Figure 3 shows experimental data obtained on smooth samples of 30HGSN2A (30ХГСН2А) steel under various modes of shot blasting hardening. A shot with diameters of 0.2 was used; 0.5; 1.0 and 2.0 mm at an air pressure of 0.1; 0.2 and 0.3 MPa. To determine the rate of collision of the shot with the surface of the samples, the experimentally obtained training schedule for this particular installation was used. As can be seen from these graphs, a certain fraction size has its own optimal impact rate, and a certain velocity has its own shot size, at which the greatest increase in cyclic durability is achieved. That is, to maximize the fatigue resistance of the part, it is necessary to choose a certain optimal combination of interrelated parameters D and v. When finally choosing their values, it is very important to take into account other requirements related to ensuring the quality and efficiency of hardening, such as the accuracy of the geometry of the part, the roughness of the surface, the presence of small holes and small galley transitions in the part, etc. First of all, this applies to the choice of the size and material of the shot. It has already been mentioned above about the influence of parameters D and v on some properties of parts and their surface layer. The nature of the influence of the shot velocity on the endurance limit of the steel part

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σ_{-1}, the maximum value of compressive residual stresses σ_{rem}, and the surface roughness parameter R_a is shown in Fig. 4.

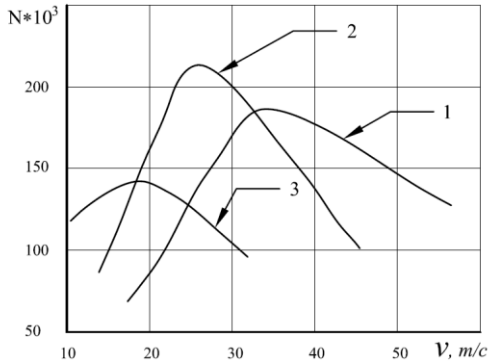

Fig. 3. Dependence of the cyclic durability of samples made of steel 30HGSN2A (30ХГСН2А) on the modes of shot blasting v and D: 1 - the diameter of the shot 0.5 mm; 2 - the diameter of the shot 1.0 mm; 2 - the diameter of the shot 3.0 mm.

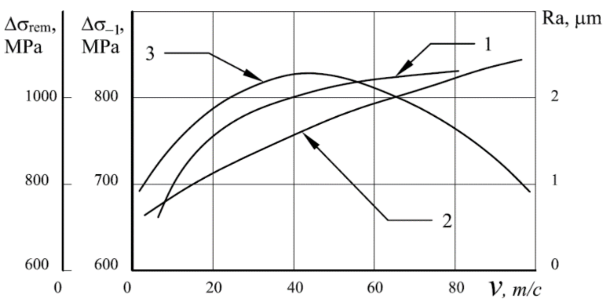

Fig. 4. Effect of the shot velocity on the residual stress in the surface layer σ_{rem} - curve 1, surface roughness R_a - curve 2 and endurance limit steel σ_{-1} - curve 3.

In order to reduce or avoid time-consuming experimental studies in the selection of optimal technological parameters of shot blasting hardening, some publications propose to use integrated, generalized parameters or criteria for assigning values D, v and t. These criteria may include a combination of individual process parameters, such as the diameter of the fraction D, the velocity of its impact v and the processing time of the surface unit t. It is assumed that the optimal values of the generalized parameter or criterion correspond to the maximum increase in the fatigue resistance of the part hardened by the shot, of course, taking into account certain boundary conditions. Knowing the optimal values of a generalized parameter, you can assign a value to one process parameter, for example, D or v, and then calculate the value of another [11].

Based on experiments found that the optimal modes of strengthening with a shot, in which the maximum endurance limit is reached, correspond to certain values v^2t or D^3v^2t. The generalized indicator D^3v^2t characterizes the total kinetic energy of the shot transferred to the material of the part during the hardening time t. However, these criteria have not found further confirmation and, as a result, industrial application.

In some works, other generalized parameters were considered, for example, in the form of the product Dv [12]. This criterion characterizes the specific kinetic energy of the shot, related to the area of the well left by the shot.

It should be noted that many publications are also devoted to theoretical estimates of the amount (fraction) of kinetic energy of the shot, which is absorbed during the first and repeated blows of the shot by the material of the part and, precisely due to which, its properties and mechanical characteristics are improved. It is noted that the coefficient of use of the kinetic energy of the shot has a complex dependence on the strength and hardness of the material of the part and the fraction itself, its speed, diameter and direction of impact relative to the hardened surface. Different factors may be taken into account in different works: the rebound energy of the shot from the part, taking into account or without taking into account the angle of impact; part of the energy spent on an instantaneous increase in the temperature of the surface layer in the impact zone; energy to overcome the resistance of a thin layer of liquid, sometimes used in hardening; energy spent on the phase transformation of the material and other factors [13].

When choosing the configuration of a generalized parameter, it is desirable to focus on physically justified combinations of technological parameters that in an "understandable" form would reflect exactly that part of the kinetic energy of the shot that is responsible for increasing fatigue resistance and, therefore, due to which new "useful" properties of the hardened surface and surface layer of the material are formed [14].

To determine the possible configuration of the generalized indicator, experimental studies were carried out on samples of steel 30 HGSN2A (30 ХГСН2А), hardened to HRC46, with a diameter in the working section of 7.5 mm. Smooth samples and samples with an annular grinding corresponding to the theoretical stress concentration coefficient $\alpha_\sigma = 1.5$, with an initial surface roughness of $R_a = 2.0$ μm, were tested. Fatigue tests were carried out on a magnetic resonance plant with a load of symmetrical bending and a loading frequency of ~ 100 Hz. The criterion for destruction was the formation of a fatigue crack with a size of 0.5 ... 1 mm. Smooth samples were tested at a cyclic voltage amplitude of $\sigma_a = 900$ MPa, samples with a voltage concentrator - at $\sigma_a = 650$ MPa. Surface hardening was carried out on a pneumatic blasting machine with steel shot. The hardening modes were selected based on the plan of the factor experiment with a fraction size of 0.2; 0.5; 1.0 and 2.0 mm, at an air pressure of 0.15; 0.20 and 0.25 MPa and processing time 120: 210 and 300 s. To increase the reliability of the results, 6 samples were tested at each point in the matrix of the factor experiment. Part of the results obtained were shown in the graphs of Fig. 3.

Variance analysis of the results of the experiment showed that in the considered ranges D, v and t, the most significant (according to Fisher's criterion with a confidence probability of 80%) are the parameters D and v. Time slightly affects the fatigue strength of the samples, since in the range under study it provides the required continuity of surface treatment. The optimal time of surface hardening can be estimated according to the method proposed in the work , the assumptions of the conditions for the need to cover the shot with prints at least, for example, 90% of the surface and not less than 2 times.The optimal time of surface hardening can be estimated according to the method proposed in the work , the assumptions of the conditions for the need to cover the shot with prints at least, for example, 90% of the surface and not less than 2 times [15].

When analyzing the results of the factor experiment, a different combination of parameters D and v was considered, proportional to the kinetic energy of the fraction, related to the depth of plastic deformation (depth of the rivet), to the volume of the plastic deformation zone under the print of the shot, to the area of the spherical print of the shot, to its perimeter, taking into account and without taking into account the rebound energy of the shot and other possible combinations[16].

Statistical analysis of the results of the experiment showed that the cyclic durability of grain-hardened samples is steadily correlated with the Dv^2 parameter. Fig. 5 shows the results of the experiment in the form of dependencies of the cyclic durability of hardened samples on the generalized parameter Dv^2. As can be seen from the graphs, these dependencies have a pronounced maximum of durability values in certain ranges of Dv^2 values. For smooth samples $(Dv^2)_{opt}$=0.6... 1.0 m^3/s^2, and for samples with voltage concentrator α_σ=1.5

$(Dv^2)_{opt}$=0.4... 0.9 m^3/s^2. Note that the same results for samples with a voltage concentrator, but constructed in different coordinates (cyclic durability N - fraction velocity V) are shown in Fig. 3. If we compare these results with the data of production instructions and technological materials of Institute of Aviation Technology, it should be noted that the recommended values of D and v coincide closely[17].

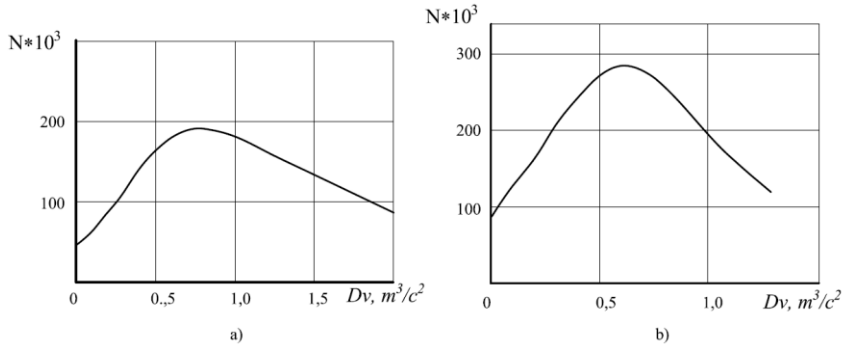

Fig. 5. Dependence of the average cyclic durability of 30HGSN2A (30ХГСН2А) steel on the generalized parameter Dv^2: a) smooth samples; voltage amplitude during tests σ_a = 900 MPa; b) samples with voltage concentrator α_σ = 1.5; voltage amplitude during tests σ_a = 650 MPa.

To further confirm the results obtained, a study of shot blast hardening (at different values D and v) of smooth samples was carried out, which, after cyclic operation at a voltage amplitude of σ_a = 900 MPa for 50 thousand cycles, in order to restore fatigue durability, were re-strengthened. Re-hardening, for all samples, was carried out in one mode with a shot with a diameter of 0.5 mm at an air pressure of 0.2 MPa. These modes are chosen based on the equipment and capabilities of aircraft repair enterprises. The high efficiency of restoring the resource of hardened parts by repeated surface hardening is confirmed, for example, in the works [18-21].

The results of the tests are shown in Fig. 6, which clearly show that the maximum cyclic durability of the samples corresponds to a certain range of the generalized indicator, that is, $(Dv^2)_{opt}$ = 0.3 ... 0.8 m^3/s^2. Comparing these results with the results presented in Fig. 5a, it can be noted that if during operation it is necessary to re-harden the parts, then the modes of the 1st shot blasting can be selected less intensive, that is, hardening can be carried out with a smaller shot and at lower air pressure.

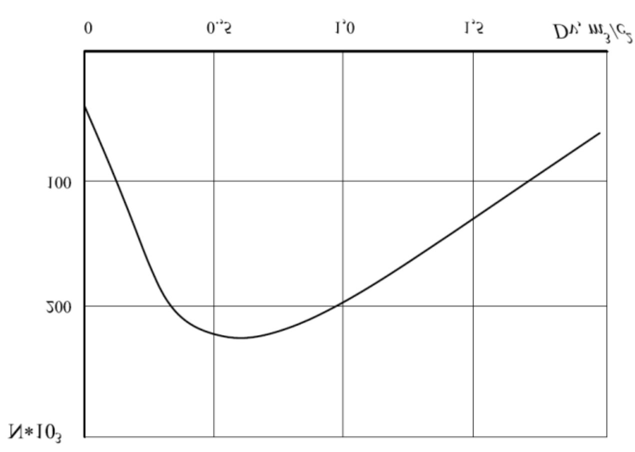

Fig. 6. Dependence of the average cyclic durability of smooth samples made of steel 30HGSN2A (30ХГСН2А) on the generalized parameter Dv^2. Samples after the 1st hardening with shot and cyclic run-in are re-strengthened.

4 Conclusion

When choosing the modes of shot blasting hardening of parts, it is necessary to take into account not only their material and geometry of the processing zones, but also the operating conditions, including the level of variable loading. It is also necessary to take into account the possibility of restoring the resource of parts during the operation of repeated shot blasting.

To select the optimal technological parameters of shot blasting hardening, which provide the greatest increase in fatigue resistance of parts made of high-strength materials and working in conditions of multicycle fatigue, it is possible to use a generalized indicator-criterion in the form of a combination of two technological parameters Dv^2.

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