Recovery of fatigue life of 30HGSN2A steel aircraft parts by repeated shot peening

G N Kravchenko, I V Gerasimov and K G Kravchenko
Moscow Aviation Institute (National Research University), Volokolamskoe highway 4, 125080, Moscow, Russia

E-mail: gnkrav@mail.ru

Abstract. An experimental estimation of the high efficiency of restoring fatigue strength and durability of prototypes and hinged-bolted joints’ eyes made of high-strength 30KHGSN2A steel by repeated peening by shot in a multi-cycle region is given. The results obtained take into account the effects of stress concentration and the statistical nature of the fatigue failure process on the recovery level and increase cyclic durability.

1. Introduction
Surface plastic deformation (SPD) methods are widely used in various branches of engineering to increase the bearing capacity of power parts and assemblies functioning in difficult operating conditions. This is primarily an increase in the characteristics of fatigue resistance, wear resistance, fretting corrosion and some other indicators of operational quality [4; 5]. This fully applies to technological methods of shot-peening, which have proved themselves not only to be highly effective methods of ensuring fatigue life and the resource of highly loaded parts, but also as very universal and low-cost production processes.

In recent years, SPD methods have been successfully used in repair technologies to restore the fatigue life of power parts during their operation and repair. Such recovery effectiveness is due to a significant improvement in the process of peening the mechanical properties and stress-strain state of the material surface layer, positive changes in its fine structure, as well as with a possible improvement in the surface microrelief. A certain role is also played by the effect of “healing” or “renewal” of a thin surface layer with fatigue microcracks that may have appeared during operation [6].

To eliminate such microcracks with the removal of a thin, “damaged” surface with a thickness of ~ 10 ... 80 μm, technological processes based on mechanical or electrolytic grinding, as well as abrasive or sandblasting of the parts’ surface, sometimes combined with the use of SPD methods, have been developed and implemented.

Repeated peening by SPD methods has shown high efficiency in restoring the endurance of power aircraft parts made of high-strength materials. When these methods are used to restore the parts’ fatigue life that have already been peened by SPD during production and have worked in operation for more than half of the technical resource [1; 2; 3].

In the majority of published works on the re-peening effectiveness, experimental studies were performed on smooth laboratory prototypes without evaluating the dispersion of the results obtained to restore their fatigue life.
In this work, experimental studies of the re-peening effectiveness with a shot in restoring the fatigue life of high-strength steel 30KHGSN2A taking into account the influence of stress concentration are carried out. Most of the fatigue tests were carried out in a statistical aspect, which allowed us to determine the restored durability dispersion indices, to construct its distribution function and, thereby, evaluate the reliability of the parts being restored.

2. Methodology
Experimental studies of evaluating the repeated shot peening effectiveness were carried out on smooth prototypes with a working diameter of 7.5 mm and a stress concentrator $\alpha_\sigma=1.5$, performed on prototypes with a diameter of 15 mm in the form of a circular undercut to a diameter of 7.5 mm and with a rounded bottom radius of 1.8 mm, as well as on eyes prototypes modeling the elements of articulated-bolted joints widely used in aircraft structures, the drawing of which is shown in figure 1. Prototypes are made of steel 30KHGSN2A with peening up to HRC46, the surface is grinded to $Ra=0.63$ μm.

![Figure 1. Fatigue test eye prototype.](image)

Surface peening was carried out on a special pneumatic shot blasting machine with steel shot. Technological modes of shot peening are determined based on the recommendations of this work. Parameters of the first peening: shot diameter is 2 mm; shot speed is 25 m/s; peening time of a prototype rotating at a speed of 5 rpm is 210 sec; the distance from the nozzle to the peened surface is 150 mm. Re-peening parameters: shot diameter is 0.4-0.6 mm; shot speed is 40 m/s; peening time is 180 sec. Fatigue tests of the prototypes were carried out on a magnetic resonance installation under loading by cantilevered bending with a frequency of 80-100 Hz until a fatigue crack formed of about 0.1-0.5 mm [7; 8].

From smooth prototypes tests it was found that the endurance limit based on $Nb=10$ million cycles of smooth prototypes with a ground surface is $\sigma_l=630$ MPa, and that of shot-peened particles with a diameter of 2 mm is 730 MPa, i.e. the first peening increased the endurance limit of grinded prototypes by 15%. Based on these results, the level of stress amplitude was chosen for comparative fatigue tests and for cyclic life before re-peening equal to $\sigma_a=900$ MPa, which was 0.55$\sigma_c$ from the breaking strength or 1.23$\sigma_l$ from the endurance limit [9].
To estimate the cyclic durability dispersion and to choose the intermediate run time duration, the distribution and the durability prototypes’ functions at the stress level $\sigma_a = 900 \text{ MPa}$ were constructed, shown in figure 2a in coordinates: the failure probability is the logarithm of the number of cycles before failure. Based on the durability dispersion, characterized by the logarithm mean square deviation of the number of cycles to failure of the peened prototypes $\sigma_{\ln N} = 0.20$, the duration of the cyclic operating time was chosen in accordance with the 10% probability of failure, which amounted to $N_{\text{life}} = 80$ thousand cycles [10].

3. Results
Variants of surface treatment of prototypes and average values of fatigue life obtained from the results of tests of 8-15 prototypes (for each variant of surface treatment) are shown in table 1 and figure 2b.

![Figure 2](image)

**Figure 2.** The results of fatigue tests of smooth prototypes made of 30KHGSN2A steel: a) cyclic durability distribution; b) cyclic durability average values’ diagrams (numbers on the diagram correspond to the serial number in table 1).

| № | Surface treatment technology | Cyclic operating time at stress $\sigma_a = 650 \text{ MPa}$ in thousand cycles | Re-peening with a diameter of mm | Cyclic durability to failure at $\sigma_a = 650 \text{ MPa}$ in thousand cycles | Mean square deviation $\sigma_{\ln N}$ |
|---|-------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------|
| 1 | grinding                      | -                               | -                               | 46                              | 0.189                       |
| 2 | shot peening with 2 mm        | -                               | -                               | 154                             | 0.205                       |
| 3 | shot peening with 2 mm        | -                               | 0.4…0.6                        | 207.5                           | 0.197                       |
| 4 | shot peening with 2 mm        | 80                              | 0.4…0.6                        | 278.5                           | 0.200                       |

From these data it follows that peening with a 2 mm fraction increased the durability of grinded by more than 3 times, and sequential prototypes’ peening with a fraction of 2 mm and a diameter of 0.4-0.6 mm (without intermediate cyclic operating time) increased their durability by another 30%. At the same time, repeated shot-blast peening increased the durability of prototypes compared to peened successively two times by 34%, and compared to peened only once by shot with a diameter of 2 mm by 80%; taking into account the intermediate cyclic operating time, the increase in the total durability was 1.7 and 2.3 times, respectively.
The surface treatment options for prototypes with a stress concentrator and the average values of fatigue life obtained from testing 8-16 prototypes for each option are shown in Table 2. Figure 3 shows the distribution functions and the durability diagrams of prototypes obtained at the amplitude of the symmetrical stress cycle \( \sigma_a = 650 \) MPa. From these results it follows that peening with a shot of 0.4-0.6 mm in diameter or 2 mm in diameter gives approximately the same increase in the durability of grinded prototypes by a factor of \( \sim 2 \). Approximately the same effect is achieved by successive peening by a shot with diameters of 0.4-0.6 mm and 2 mm without intermediate cyclic operating time. Peening with a 0.4-0.6 mm shot of grinded prototypes after cyclic production \( N_{\text{operat}} = 40 \) thousand cycles completely restores their original durability.

**Table 2.** The program and the results prototypes’ fatigue tests with a stress concentrator \( \alpha \sigma = 1.5 \).

| №  | Surface treatment technology | Cyclic operating time at stress \( \sigma_a = 650 \) MPa in thousand cycles | Re-peening with a diameter of mm | Cyclic durability to failure at \( \sigma_a = 650 \) MPa in thousand cycles | Mean square deviation \( S_{\text{hlN}} \) |
|----|-------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|----------------|
| 1  | grinding                      | -                                               | -                              | 88.8                            | 0.217          |
| 2  | shot peening with 2 mm        | -                                               | -                              | 149                             | 0.215          |
| 3  | shot peening with 2 mm        | -                                               | -                              | 126                             | 0.210          |
| 4  | shot peening with 2 mm        | -                                               | 0.4…0.6                        | 143.2                           | 0.212          |
| 5  | shot peening with 2 mm        | 80                                              | 0.4…0.6                        | 218.8                           | 0.170          |
| 6  | grinding                      | 40                                              | 0.4…0.6                        | 89.5                            | 0.205          |

**Figure 3.** Results of fatigue tests of prototypes with stress concentrator \( \alpha \sigma = 1.5 \) from 30KhGSN2A steel: a) distribution of cyclic durability; b) diagrams of average cyclic durability values (numbers on the graph correspond to the serial number in Table 2).

Re-peening increases the durability of once-peened prototypes after an operating time of \( N_{\text{operat}} = 0.5 = 80 \) thousand cycles by 50%, and taking into account the operating time it is almost two times more. In addition, re-peening somewhat reduces the dispersion of the prototypes’ cyclic durability.
Articulated bolted joints are widely used in aircraft structures. The main elements that determine the strength and reliability of these connections are bolts, forks and eyes. In the eyes, the places of the main stress sources concentration are strengthened – walls and chamfers of holes, fillets in the base, etc.

To estimate the effectiveness of re-peening, fatigue tests were carried out on eye prototypes made from forgings of 30KHGSN2A steel and heat treated after machining to HRC45. Fatigue tests were carried out on a hydro-pulsation machine with a loading frequency of 670 cycles per minute with a maximum cycle stress of $\sigma_{\text{max}} = 450$ MPa and a cycle asymmetry coefficient of $R = 0.2$.

In the eyes, planes were strengthened around the holes, the walls and the chamfers of the hole itself. The first peening was carried out by a shot with a diameter of 1.0 mm at an air pressure of 0.15 MPa; repeated made by shot with a diameter of 0.4 ... 0.6 mm at an air pressure of 0.2 MPa.

The experimental program, the cyclic operating time conditions between the first and repeated peening, and the results of fatigue tests are shown in table 3. The average cyclic durability of the eyes to failure is compared in the diagram (look at figure 4).

From the results of the experiment it follows that as a result of repeated peening, the total (taking into account the operating time) eyes durability increased by 1.5 ... 2.0 times in comparison with once peened eyes with an increase in the level and duration of the intermediate cyclic operating time, the effectiveness of repeated peening increases.

Re-peening of eyes in which a molybdenum disulfite-based coating was applied to the surface of the hole and chamfers after the first shot peening was not effective. This, apparently, is due to the fact that with small fractional impact energy, the applied coating protects the metal surface from peening.

**Table 3.** The program and the results of the eyes’ fatigue tests.

| № | Technology for processing chamfers and eye's holes | Cycle Modes $\sigma_{\text{max}}$, MPa | Re-peening with a diameter of mm | Cyclic durability to failure at $\sigma_{\text{max}}=450$ MPa in thousand cycles |
|---|---------------------------------------------------|------------------------------------------|----------------------------------|--------------------------------------------------|
| 1 | shot-peening bores                                | -                                        | -                                | 29.0                                             |
| 2 | shot peening with 1.0 mm                          | -                                        | -                                | 71.0                                             |
| 3 | shot peening with 1.0 mm                          | 450                                      | 0.4-0.6                          | 68.3                                             |
| 4 | shot peening with 1.0 mm                          | 450                                      | 0.4-0.6                          | 79.2                                             |
| 5 | shot peening with 1.0 mm                          | 500                                      | 0.4-0.6                          | 104.8                                            |

5
Figure 4. Diagram of eyes’ cyclic durability at maximum stresses of $\sigma_{\text{max}}=450$ MPa: 1 is rolling; 2 is shot peening; 3 is shot peening + cyclic operating time at $\sigma_{\text{max}}=450$ MPa + shot peening; 4 is shot peening + cyclic operating time at $\sigma_{\text{max}}=500$ MPa + shot peening.

4. Conclusions

Based on the studies, the following conclusions can be made:

- Re-peening by shot not only completely restores the durability of peened prototypes and eyes made of 30KHGSN2A steel after cyclic operating time, but also increases it from the initial value from 1.2 to 1.8 times, and taking into account the operating time from 1.8 to 2, 3 times.
- Re- peening in the stress concentrator zone in the form of a groove with a rounding radius of 1.8 mm ($\alpha = 1.5$) showed efficiency in increasing the durability of prototypes by 1.2 times and taking into account the operating time by 1.7 times.
- The first and repeated peening by shot practically does not change the dispersion of the prototypes’ fatigue life in comparison with the initial state (grounded surface); the mean square deviation of the logarithm of the number of cycles to failure lies in the range of values $\text{S}l_{\text{gN}} = 0.195 - 0.215$. A slight decrease in the durability dispersion after repeated peening is observed in prototypes with a stress concentrator with $\text{S}l_{\text{gN}} = 0.17$.
- Re-peening of the eyes increases their cyclic durability by 1.5–2 times compared to once-strengthened eyes and by 3.5–5 times compared to unstrengthened (holes and chamfers in which there were after boring).
- Re-peening with a shot significantly increases the initial specimens’ and eyes’ durability out of 30KHGSN2A steel only if they are subjected to cyclic loading between the first and second peelings.
- Repeated peening by shot can be a highly efficient and at the same time universal and low-cost technological method for restoring the fatigue strength and durability of power parts of high-strength steel aircraft structures.

References

[1] Boytsov B V, Rykovskiy B P and Kravchenko G N 1981 Efficiency of re-hardening of high-strength structural materials 30KHGSN2A and VT22 Vestn. mash. 3 12-3
[2] Kravchenko G N 1991 Increased durability of parts by repeated bead-hardening Nad.’ i kontr. kach. 10 12-4
[3] Kravchenko G N and Kravchenko K G 2018 The restoration of the durability of the power parts of the aircraft by repeated surface plastic deformation Pol. 4 37-44
[4] Yang D and Liu Z 2015 Surface plastic deformation and surface topography prediction in peripheral milling with variable pitch end mill Int. journ. of mach. tool. And man. 91 43-53
[5] Unal O and Varol R 2015 Surface severe plastic deformation of AISI 304 via conventional shot
peening, severe shot peening and repeening \textit{Appl. surf. scienc.} \textbf{351} 289-95

[6] Payet M, Marchetti L, Tabarant M and Chevalier J P 2015 Corrosion mechanism of a Ni-based alloy in supercritical water: Impact of surface plastic deformation \textit{Corr. scienc.} \textbf{100} 47-56

[7] Capraz O O, Ide S, Shrotiya P and Hebert K R 2016 Tensile stress and plastic deformation in aluminum induced by aqueous corrosion \textit{Act. mat.} \textbf{115} 434-41

[8] Settgast C, Abendroth M and Kuna M 2019 Constitutive modeling of plastic deformation behavior of open-cell foam structures using neural networks \textit{Mech. of mat.} \textbf{131} 1-10

[9] Pohl F, Mottyll S, Skoda R and Huth S 2015 Evaluation of cavitation-induced pressure loads applied to material surfaces by finite-element-assisted pit analysis and numerical investigation of the elasto-plastic deformation of metallic materials \textit{Wear.} \textbf{330} 618-28

[10] Bhuiyan M S H., Choudhury I A, Dahari M, Nukman Y and Dawal S Z 2016 Application of acoustic emission sensor to investigate the frequency of tool wear and plastic deformation in tool condition monitoring \textit{Meas.} \textbf{92} 208-17