To the definition of stress-strain state of springs during recovering when hardened

N A Zemlyanushnov* and N Y Zemlyanushnova  
North-Caucasus Federal University, 1 Pushkina Street, Stavropol, 355009, Russia

*nikita3535@mail.ru

Abstract. The results of experimental work on the recovering of springs are presented. A methodology is proposed for theoretical determination of the parameters of springs during recovering using low-temperature thermomechanical treatment (tension with heating), shot peening and contact hardening.

1. Introduction

High requirements for reliability, durability and quality of parts, as well as for the operational qualities of automobile transport, the need for resource saving in the motor transport complex determine the task of improving the technology of automobile springs recovering [1, 2]. For example, the performance requirements of a valve spring imply that it must not fail by fracture or by load, relaxation loses so much of its controlling force that it fails to maintain control between a tappet and a cam [3].

Therefore, the development and introduction of new technologies of the recovering of high load compression springs remain of current interest.

2. Results and Discussion

To solve this problem, together with the employees of the ‘Avtonormal’ Belebeevsky Plant’ Joint-Stock Company (‘BelZAN’), three options of the technology for the recovering of springs made of a hardened spring wire [4] have been developed and experimentally justified, see Table 1. An inner valve spring 2101-1007021 has been used as a laboratory sample. Such strengthening operations as contact hardening and shot peening have taken place.
Table 1. Options for technologies of 2101-1007021 springs strength recovering.

| No. | Option 1                                                                                                                   | Option 2                                                                 | Option 3                                                                 | Remarks, equipment                                                                 |
|-----|---------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| 1   | Control: $l_2 = 20$ mm, $F_2=275.4\pm13.7$ N                                                                             |                                                                         |                                                                         | $TLS-S-2000$ scales made by $TIME$                                                   |
| 2   | Endurance testing to cyclic loads from $l_0$ to $l_2$ 6×10⁶ cycles                                                      |                                                                         |                                                                         | $SBN 0121$ test stand                                                              |
| 3   | Rinse (grease removal)                                                                                                      |                                                                         |                                                                         | -                                                                                   |
| 4   | Control: $l_2 = 20$ mm, $F_2=275.4\pm13.7$ N                                                                             |                                                                         |                                                                         | $TLS-S-2000$ scales                                                               |
| 5   | Mandrel heating: $T=420^\circ C$ (heating temperature), period of heating makes 15 minutes                               |                                                                         |                                                                         | Laboratory furnace                                                                |
| 6   | Tension. Spring operating portion height makes 45 mm                                                                     |                                                                         |                                                                         | Device for spring extension                                                         |
| 7   | Mandrel tempering: $T=400^\circ C$, period of tempering makes 30 minutes                                                  | Mandrel tempering: $T=420^\circ C$, period of heating makes 40 minutes |                                                                         | Laboratory furnace                                                                |
| 8   | Contact hardening with the load of 3100 N $(10F_3)$                                                                     |                                                                         |                                                                         | Device for spring contact hardener                                                 |
| 9   | Tempering: $T=400^\circ C$, period of tempering makes 30 minutes                                                         |                                                                         |                                                                         | Laboratory furnace                                                                |
| 10  | Shot peening: CSS-0.5, test plate flexure makes 0.3 mm                                                                  | Shot peening: CSS-0.5, test plate flexure makes 0.3 mm                  |                                                                         | $6GT8.5-10R$ machine made by Carlo Banfi                                         |
| 11  | Contact hardening with the load of 3100 N $(10F_3)$                                                                      | Contact hardening with the load of 12400 N $(40F_3)$                     |                                                                         | Device for spring contact hardener                                                 |
| 12  | -                                                                                                                                         | -                                                                       | Tempering: $T\leq240$ °C, period of tempering makes 30 minutes           | Laboratory furnace                                                                |
| 13  | -                                                                                                                                         | -                                                                       | Contact hardening with the load of 3100 N $(10F_3)$                       | Device for spring contact hardener                                                 |
| 14  | Control: $l_2 = 20$ mm, $F_2=275.4\pm13.7$ N                                                                             |                                                                         |                                                                         | $TLS-S-2000$ scales                                                               |
| 15  | Endurance testing to cyclic loads from $l_0$ to $l_2$ 10.5 × 10⁶ cycles                                                  |                                                                         |                                                                         | $DV8-S2$ test stand made by Georg Reichert                                             |
| 16  | Control: $l_2 = 20$ mm, $F_2=275.4\pm13.7$ N                                                                             |                                                                         |                                                                         | $TLS-S-2000$ scales                                                               |

Remark: $l_0$, $l_2$ – correspondingly, spring free height and at operating load, mm; $F_2$ – spring operating load, N; $F_3$ – spring strength until the coils touch, N; CSS-0.5 – cast steel shot with the diameter of 0.5 mm.
All recovered springs passed endurance tests to cyclic loads without unacceptable cambers and breakdowns. The tests were stopped after 10.5×10^6 cycles, which was 1.75 times higher than the norm for springs in the amount of 6×10^6 cycles. The test results are listed in Table 2.

**Table 2.** Results of experimental works on recovering of load bearing characteristics of the 2101-1007021 valve springs.

| No. | Before tests | After 6×10^6 test cycles | After recovering | After 10.5×10^6 repeated test cycles |
|-----|--------------|--------------------------|------------------|--------------------------------------|
|     | F_2, N       | F_2, N                   | ΔF_2/F_2, %      | F_2, N                               | ΔF_2/F_2, %      |
|     | min          | 279.6                    | 1.3              | 274.8                                | 0.8              | 866.0                       | 274.4                       | 0                          |
|     | max          | 290.6                    | 3.7              | 293.6                                | -4.1             | 926.0                       | 292.8                       | 1.4                        |
|     | X            | 283.4                    | 2.0              | 281.2                                | 0.9              | 884.0                       | 279.9                       | 0.45                       |
|     | R            | 11.0                     | 6.4              | 18.8                                 | 4.9              | 60.0                        | 18.4                        | 1.4                        |
| Option 1 for technologies | |                       |                  |                                      |                  |                            |                            |                            |
|     | min          | 271.2                    | 0.6              | 266.6                                | 0.1              | 840.0                       | 262.4                       | 0.5                        |
|     | max          | 285.4                    | 4.7              | 288.2                                | -6.0             | 909.0                       | 281.0                       | 2.5                        |
|     | X            | 277.0                    | 2.1              | 276.0                                | -1.8             | 870.3                       | 271.7                       | 1.6                        |
|     | R            | 14.2                     | 16.0             | 21.6                                 | 6.1              | 69.0                        | 18.6                        | 2.0                        |
| Option 2 for technologies | |                       |                  |                                      |                  |                            |                            |                            |
|     | min          | 276.0                    | 1.03             | 290.6                                | -2.2             | 916.0                       | 288.2                       | -0.7                       |
|     | max          | 291.0                    | 1.94             | 316.0                                | -15.2            | 996.0                       | 316.6                       | 1.0                        |
|     | X            | 283.7                    | 1.58             | 302.2                                | -8.3             | 953.0                       | 302.1                       | -0.2                       |
|     | R            | 15.0                     | 16.2             | 25.4                                 | 13.0             | 80.0                        | 28.4                        | 1.7                        |
| Option 3 for technologies | |                       |                  |                                      |                  |                            |                            |                            |

**Remark:** symbol ‘-’ in the Table shows the increase in the spring strength; τ_2 – shear stress at operational deformation, MPa; X – arithmetical average; min – minimum value of selection; max – maximum value of selection; R – swing amplitude.

A theoretical justification for the spring recovering option 2 is well-known [4]. The equation for determining the boundary separating the elastic zone from the plastic one in the cross section of the coil at contact hardening is as follows [5]:

\[
3 \left( \frac{\Delta \kappa \cdot G \cdot x_0}{\sigma_m} \right)^2 + 3 \left( \frac{\Delta \kappa \cdot G}{\sigma_m} \right)^2 \left( r - y_0 \right)^2 + \frac{C \cdot y_0^6}{\left( \lambda^2 + b^2 \cdot y_0^2 \right)^2 \cdot \sigma_m^2} = 1, \tag{1}
\]

where Δκ is spring coil torsion increment, mm⁻¹;
G is modulus of elasticity in shear, MPa;
x₀, y₀ are positions of points (Figure 1) belonging to the elastic boundary, mm;
r is spring wire radius, mm;
b is half-width of the contact line of the coils, mm;
λ is elliptic coordinate, mm² [6], which is determined as a positive root from the following equation:

\[
\frac{x^2}{b^2 + \lambda} + \frac{y_0^2}{\lambda} = 1,
\]
where \( E \) is modulus of elasticity, MPa.

\[
C = \frac{A^2 \cdot b^4 \cdot (b^2 + \lambda)}{\lambda}, \quad \text{constant} \quad A = \frac{1,727 \cdot E}{\pi \cdot r},
\]

\( \lambda \) is elliptic coordinate, mm², which is determined as a positive root from the following equation:

\[
\frac{x^2}{b^2 + \lambda_1} + \frac{y^2}{\lambda_1} = 1,
\]

where \( x, y \) are coordinates of the point in the plastic zone, at which stress values are determined, mm;

\( Z \) is value characterizing the depth of plastic hardening along the cross section of a spring coil [6];

Torque [5] is as follows:

\[
\tau_{sp} = \frac{\Delta \kappa \cdot G \cdot \sqrt{x^2 + \left(\frac{d}{2} - y\right)^2}}{Z},
\]

Expressions to determine the stress state of the spring coil during contact hardening [5] are as follows:

\[
\sigma_y = X \cdot \frac{E \cdot y_{0e}^3}{\left(\lambda^2 + b^2 \cdot y_{0e}^2\right)} + E_1 \left(X_1 \cdot \frac{y^3}{\left(\lambda_1^2 + b^2 \cdot y^2\right)} - X \cdot \frac{y_{0e}^3}{\left(\lambda^2 + b^2 \cdot y_{0e}^2\right)}\right),
\]

\( \tau_{sp} \) is torsional stresses, MPa.
\[
M_{sp} = \int_S \tau \cdot \rho dS = \int_S \left( \Delta \cdot \left( x^2 + \left( \frac{d}{2} - y \right)^2 \right) \right) dS,
\]
where \( S \) is coil cross-sectional square, mm\(^2\);
\( \rho \) is polar radius of the examined point of the coil cross section, mm.

Spring diameter increment, mm, [5] is as follows:
\[
\Delta D = \frac{D^2 \sin \alpha}{\cos \alpha} \cdot \left( \Delta \kappa - \frac{32 \cdot M_{sp}}{G \cdot \pi \cdot d^4 \cdot K} \right),
\]
where \( D \) is average spring diameter before hardening, mm;
\( \alpha \) is angle of the spring coils before hardening, degrees;
\( K \) is coefficient correcting for the difference between the average torsion increment of the wire fibers and the torsion increment of the spring wire axis during initial compression due to different angles of elevation of the fibers at different points of the coil section.

Variation of spring test portion height [5], mm, is as follows:
\[
\Delta l_{pat} = L_{pat} \cdot \frac{D}{2} \cdot \cos \alpha \cdot \left( \Delta \kappa - \frac{32 \cdot M_{sp}}{G \cdot \pi \cdot d^4 \cdot K} \right),
\]
where \( L_{pat} \) is spring test portion sweep length, mm.

Let us consider the theoretical justification of the third option for the spring recovering (Table 1). Here, it is necessary to determine the effect of shot peening, as well as subsequent contact hardening, on the parameters of the springs after they are stretched and tempered. The parameters of the springs depend on the size of the elastic part remaining after hardening. It was shown in [7] that the internal fibers of the springs are riveted in the same way as the external ones — until being saturated, therefore, the depth of hardening will be the same over the cross section of the spring coil.

From the observations presented in [8], it follows that displacements under the surface are approximately radial with respect to the point of the initial contact, and the equal deformations surfaces are approximately hemispherical in their shape. In this simplified model of elastoplastic insertion, the contact surface is assumed to be covered by a hemispherical core of radius \( a \) (Figure 2). The presence of a hydrostatic stress state with the intensity of \( \sigma_p \) is supposed inside the core.

Figure 2. Spherical core model to analyze the introduction of a sphere into an elastoplastic half-space.
The radial $\sigma_r$ and peripheral $\sigma_Q$ of the plastic zone tension, MPa, $a \leq r_i \leq c$ (Figure 2), are determined by the dependences [8]:

$$
\sigma_r = \left[ -2 \times \ln \left( \frac{c}{r_i} \right) - \frac{2}{3} \right] \times \sigma_m,
\sigma_Q = \left[ -2 \times \ln \left( \frac{c}{r_i} \right) + \frac{1}{3} \right] \times \sigma_m
$$

(7)

where $c$ is the boundary separating the elastic zone from the plastic one, mm;
$r_i$ is the distance from the center of the introduced shot to the examined point of the hardened material, mm.

In the elastic zone, $r_i \geq c$ [8]:

$$
\sigma_r = -\frac{2}{3} \times \left( \frac{c}{r_i} \right)^3 \times \sigma_m,
\sigma_Q = \frac{1}{3} \times \left( \frac{c}{r_i} \right)^3 \times \sigma_m
$$

(8)

The onset of full plasticity occurs at the upper limit for the penetration pressure $p_m = 3\sigma_m$, which is achieved for the sphere at [8]

$$
\frac{E^* \times a}{\sigma_m \times R_o} \approx 30,
$$

(9)

where $R_o$ is the shot radius, mm.
$E^*$ is the modulus of inelastic buckling, MPa.

The position of the elastoplastic boundary is determined by the following correlation [8]:

$$
\frac{c}{a} \approx 2.3
$$

(10)

Using the expressions (7) ... (10), it is necessary to determine the depth of hardening $c$ of the springs at shot peening. For example, from the analysis performed according to dependences (7) ... (10) [4], it follows that the depth of hardening (riveting) of the 2101-1007021 valve springs during shot peening at BelZAN JSC makes 0.212 mm (Figure 3). This output coincides with the results of experiments and calculations given in [7, 9] (with $c = 0.21$ mm).

The strength and geometric parameters of the springs at plastic hardening depend on the square of the remaining workable part, that is the elastic core (Figure 3). When shot peening a spring in a free condition, the inner and outer fibers are riveted till they get their saturation. Therefore, the elastic core of the spring in the cross section is a circle of diameter $d_{imp} = d - 2c$. When hardening, the elastic core is an ellipse [6].

Figure 3. Spring coil cross section at shot peening and at hardening.
Using the expressions (1) ... (6) presented in this work, it is necessary to establish the dependence of the recovered spring geometrical parameters on the hardening load and to determine the square of the elastic core of the spring wire cross section. The compression of the spring at shot peening should be determined according to the graph of the dependence of the height of the test portion of the hardened spring on the square of the coil section elastic core [4].

Using the same expressions (1) ... (6), it is necessary to study the stress-strain state of the spring after shot peening with hardening with a load of $10F_3$ (Table 1, Option 3). The subsequent tempering after shot peening treatment at a temperature of $\leq 240$ ° C does not lead to a significant change in the residual stresses either in magnitude or in the depth of their propagation [9]. Here, it is necessary to introduce the increase in the yield strength of the spring material in the plastic zone after shot peening (Fig. 3). When calculating the stress-strain state of the spring during contact hardening [4, 10], it is necessary to take the yield strength as the equal one to the tensile strength of the spring material for the hardened zone after shot peening treatment.

3. Conclusion
The proposed methodology for studying the stress-strain state and determining the parameters of the springs is recommended to be used when developing a technology for the restoration of expensive springs, such as vehicle suspension springs.

Acknowledgments
The reported study was funded by the Russian Fund of Assistance of Innovation according to research project No. 7731p/11336.

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