

Method of experimental study of the force-deformation characteristics of the Belleville spring of the stop assembly of a direct-flow gate valve

Metoda eksperymentalnego badania charakterystyki siła-odkształcenie sprężyn Beleville w zespole odcinającym zasuwę klinowej

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ABSTRACT: The article presents research methods and appropriate equipment for conducting experiments, as well as the analysis of the results. Studies on the hardness of the microstructure, elastic deformation and parts and samples were carried out using hardness testers, microscopes PMT-3, MIM-8 and devices for measuring the “force-strain” characteristic. The results of the study were used to establish the dependence of the elastic properties of Belleville springs on the heat treatment modes, while also determining the microstructure and layer depth using various research methods. Every work studying the elastic properties and measurement of the static compressive force of a spring at a given strain value has been studied theoretically. Depending on the operating conditions, disc springs can be installed singly or assembled into packages, forming an elastic element working under compression. The research materials will be used in the work to improve the tightness of straight-through valves and the durability of the shut-off assembly parts. The dependence of the spring compression force and its deformation on the geometrical parameters of the disc springs has been established. Comparison of experimental and theoretical dependences has been made. It has been established that the residual deformation of the Belleville spring after captivity has a negative effect on the tightness of the shut-off valve assembly. The influence of various technological processes and modes of thermal treatment of disc springs on their elastic properties has been studied. Practical recommendations for improving the technological process of thermal treatment of Belleville springs have been proposed. The tasks of further research and implementation of the obtained results have been determined. Search work has been carried out to improve the technology of hardening processing of parts of the shut-off unit (gate and seat) of direct-flow valves. The possibility of using accelerated nitrocarburizing in a triethanolamine medium with induction heating by high-frequency currents at a temperature range of 950°C for boriding and borochroming has been established. Samples were made from standard steel grades 40, 40Kh and 38Kh2MYuA, subjected to hardening by the considered methods, and a study was made of the hardness, depth and microstructure of the hardened layer. Research in this direction should be continued in order to study the tribological characteristics (friction coefficient and wear resistance) of hardened parts. Each operation of the spring manufacturing technology has been studied, and deviations that have a significant impact on the operation of the spring and the sealing of the shut-off valve assembly have been identified.

Key words: technology, heat treatment, hardening, Belleville spring, elasticity, force-deformation, hardness, microstructure.

STRESZCZENIE: Artykuł przedstawia metody badawcze i odpowiednie wyposażenie służące do przeprowadzania eksperymentów, a także analizę wyników. Badania przeprowadzono przy użyciu testerów twardości, mikroskopów PMT-3, MIM-8 oraz urządzeń do pomiaru charakterystyki “siła-odkształcenie”. Wyniki tych badań wykorzystano do ustalenia zależności właściwości elastycznych sprężyn Belleville od parametrów obróbki cieplnej, jednocześnie określając mikrostrukturę i głębokość warstwy za pomocą różnych metod badawczych. Każdy przypadek badania właściwości elastycznych i pomiaru statycznego siłowego odkształcenia sprężyny przy danej wartości odkształcenia był analizowany teoretycznie. W zależności od warunków pracy sprężyny tarczowe mogą być montowane pojedynczo lub w pakietach, tworząc element elastyczny podlegający ścisnaniu. Materiały badawcze mogą zostać wykorzystane w pracach mających na celu poprawę szczelności zasuw oraz trwałości części zespołu zamykającego. Ustalono zależność między siłą kompresji sprężyny i jej odkształceniem a parametrami geometrycznymi sprężyn tarczowych. Dokonano porównania wyników eksperymentalnych i teoretycznych. Ustalono, że szczytkowe odkształcenie sprężyny Belleville po jej zamontowaniu ma negatywny wpływ na szczelność zespołu zaworu zamykającego. Zbadano wpływ różnych procesów technologicznych i trybów obróbki cieplnej sprężyn tarczowych na ich właściwości elastyczne. Zaproponowano praktyczne zalecenia w celu poprawy procesu technologicznego obróbki cieplnej sprężyn Belleville. Określono cele dalszych badań i sposób wdrożenia uzyskanych wyników. Przeprowadzono prace badawcze w celu poprawy technologii hartowania części zespołu zamykającego (zasuwę i gniazda) zasuw klinowych. Sprawdzone możliwość zastosowania przyspieszonego azotonawęglania w środowisku trietanolaminy z indukcyjnym ogrzewaniem prądem o

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wysokiej częstotliwości w zakresie temperatury 950°C w procesie borowania i borochromowania. Wykonano próbki ze standardowych gatunków stali 40, 40Kh i 38Kh2MYuA, które poddano hartowaniu przy rozważanych metodach, przeprowadzono badanie twardości, głębokości i mikrostruktury warstwy hartowanej. Badania w tym kierunku powinny być kontynuowane w celu zbadania charakterystyk tribologicznych (współczynnika tarcia i odporności na zużycie) hartowanych części. Przeanalizowano każdą fazę technologii produkcji sprężyny i zidentyfikowano odchylenia, które mają znaczący wpływ na działanie sprężyny i uszczelnienie zespołu zaworu zamykającego.

Słowa kluczowe: technologia, obróbka cieplna, hartowanie, sprężyna Belleville, sprężystość, siła-odkształcenie, twardość, mikrostruktura.

Introduction

The development and experimental investigation of methods for increasing the “force-deformation” characteristic of the Belleville spring of a direct-flow valve shut-off device and the structural strength of gas and oilfield equipment parts are presented below.

Problem statement

To study the effect of tightness and wear resistance on reliability, it is advisable to determine the most typical product that possesses generalizing features inherent in most units of oilfield equipment and is distinguished by sufficient structural and technological complexity, as well as a variety of modifications. Manufacturing quality, which decisively affects performance, is functionally crucial for equipment.

The most critical component determining the operability of the valve, is the shut-off node. Wear or damage to the working surfaces of the gate valve seats, or the elastic properties of the Belleville spring, can lead to depressurization of the shut-off unit and the subsequent failure of the valve. It can be concluded that an increase in the structural strength of these components greatly enhances the reliability and durability of the valve.

Field tests of Christmas trees show that the primary cause of the deterioration of the initial state of the sealing surfaces of the locking elements and the tightness of the gate valves is the presence of a significant amount of sand in the produced product. The wear resistance of X-mas tree valve parts largely depends on the performance of Belleville springs, taking into account their properties and the size of the valve components.

Problem solution

It is known that ensuring reliable tightness of gate valves at the initial moment of operation requires a certain preliminary specific load on the sealing surfaces of the gate and seat. This load results from the deformation of the Belleville spring, and the value of this preliminary deformation depends on valve's performance.

To maintain stable characteristics of tribocoupling, it is necessary to ensure that the gate saddle is such that the disc springs do not exhibit deviations in thickness, i.e. the thickness of the springs must be held within tight tolerances at the design stage. During the manufacturing process, springs undergo plastic deformation and hardening. The residual deformation will subsequently affect the spring's elastic behavior (deformation) during operation. Therefore, the drawing must strictly prohibit residual deformation with a tolerance of up to 2.7 mm without any visual capacitation. The operating conditions of X-mas trees possess specific features that distinguish them from other machines and equipment.

Based on Belleville springs (2003), Hasanov (2016) and Guliyev and Sharifova (2019), results on Belleville springs for the direct-flow valve ZMS165x210 were obtained and analyzed. This analysis included an assessment of the technical requirements for Belleville springs according to the drawing and according to GOST 3057 standard “Belleville springs” (2003). Suggested and substantiated recommendations for adjusting the technical specifications of the drawing were applied. It was determined that the spring blank drawing should significantly differ from the drawing for the finished spring since the geometric shape and dimensions of the spring change in the process of captivity. Consequently, a spring blank drawing and its associated technical requirements were developed. Each step in the spring manufacturing technology was examined, identifying deviations that have a significant impact on the spring's performance and the sealing of the shut-off valve assembly.

The factory heat treatment technology for a spring made of steel 65 G was evaluated. It was established that this technology did not meet the requirements of the GOST standard and the drawing, significantly compromising the sealing of the locking unit, especially at low pressures ranging from 2.5 to 5 MPa.

Necessary equipment has been developed, along with recommendations for improving the quality control system for the manufacture of Belleville springs. It was determined that more than 50% of the springs exhibited technological defects.

To improve the quality of springs, meet the requirements of the GOST and the drawing, and reduce technological defects, further theoretical and laboratory studies are needed in order to:

1. empirically establish the “force-deformation” characteristic, along with the effect of residual deformation on the sealing of the shut-off valve assembly;

2. study the impact of heat treatment on permanent deformation and stabilization of the elastic properties of the spring;
3. develop recommendations for modifying the drawing and technical requirements for springs, as well as their heat treatment processes.

The technological processes for hardening the components of the shut-off assembly of X-mas tree valves in order to increase their reliability were also considered. The most optimal methods were found to be accelerated heating of HDTV, boriding and boron chroming. Samples were fabricated from steels 40, 40Kh and 38Kh2MYuA using the selected methods of strengthening the microstructure of steels, hardness, and depth of the hardened layer.

In this regard, specimens were made in shapes and sizes suitable for testing on this machinery, using standard steel grades 40, 40Kh and 38Kh2MYuA.

The hardening of the samples was carried out under the following modes (Urbanovich, 2000):

1. nitrocarburizing in a triethanol medium with high-frequency current induction heating at a temperature of 1050°C, with an exposure time of 150 s;
2. single-phase boriding – at a temperature of 950°C, with an exposure time of 4 hours;
3. two-phase boriding – at a temperature of 950°C, with an exposure time of 4 hours;
4. borochrome plating – boron plating at 950°C, with an exposure time of 4 hours, chromium plating at 1050°C, with an exposure time of 4 h.

The hardness and microstructure of the hardened layer were studied using PMT-3 and MIM-8 microscopes.

The microstructure of the samples after nitrocarburizing in triethanolamine showed that at a depth of ~300 μm (carbonitride layer), the structure consists of fine acicular martensite. There is a troostite structure under this layer and a sorbitol structure is observed closer to the core. The microstructure of the core corresponds to the ferrite-pearlite structure. The size of austenite grain according to GOST 5639 standard corresponds to 8 points.

In some areas, the separation of the ferrite grid is noticeable, and residual austenite is observed in the structure of the surface layers of some samples.

The microstructure of samples subjected to single-phase boronization exhibits a white layer on the surface, which is Fe₂B boride. Borides have the form of columnar crystals that propagate deep into the steel. Beneath the light (boride) layer, the sample structure consists of ferrite and pearlite, with ferrite located along the boundaries of pearlite grains. The microstructure of two-phase borated samples consists of a light layer consisting of FeB and Fe₂B. Here, the boride layers also have the form of columnar crystals propagating deep into the metal.

In this case, iron boride FeB is formed on the surface, followed by a layer of boride and, finally, a solution of boron in iron.

The study of the microstructure of samples subjected to boriding and chromium plating showed the presence of light layers that vary slightly from one another. On the surface there is a non-etching layer consisting of the Cr₂B phase. Beneath it, iron borides – FeB and Fe₂B – are successively located. Closer to the core, the structure of the samples consists of ferrite and pearlite. Moreover, ferrite is located along the boundaries of pearlite grains.

Problem solution method

We have conducted a comprehensive review of every work that studies the elastic properties and measurement of the static compressive force of springs at specific deformation values. Depending on the operating conditions, disc springs can be installed singly or assembled into packages, forming an elastic element working under compression. The arrangement of prefabricated packages of Belleville springs (Mildin et al., 2011) has been examined and a method for calculating the main parameters and the dissipation coefficient of a Belleville deforming device has been presented. This calculation accounts for friction forces in relation to a single ring lift. A well-known device was used to determine proximity (Androno et al., 2008). Here, the device serves to record the microdisplacement of rough solid bodies in contact under load conditions. Flat springs (dish-shaped) serve to connect the lever to the base (Zimmermann et al., 2015).

Equipment for testing springs with a static load from numerous foreign companies was used. Despite variations in design, these machines are built on the same principles as domestic ones. Most of them work based on a given deformation principle (Goren et al., 2013)

The study of the elastic properties of disc springs manufactured by the plant is carried out in five batches. Each batch comprises five current samples of a small volume, totalling 50 pieces in one sample. It is known from the theory of mathematical statistics that such a sample gives the most reliable results (Nermoen et al, 2013). The measurement of the static compressive force of the spring at a given value of deformation was carried out on a specially designed and manufactured device.

The device consists of a bottom plate 1 connected by means of two racks 2, washers 3, and nuts 4 to the top plate 5, into which a nut 6 with a pressure screw 7 is pressed on the top end of the spring. An indicator is fixed in the plate in such a way that, without load (spring deformation), its indication (tension) would be 1 mm. A stand 12, a dynamometer 8 and an indicator 9 are installed on the plate 10 to record the amount

of deformation of the dynamometer bracket, i.e. the value of the static load on the dynamometer (Figure 1).

In the initial position (without load) “0”, the marks of the scale of indicators 11 and 12 align with the pointer of the large arrow of the indicators. To measure the static force, exemplary portable dynamometers for measuring the compression of static loads with limiting forces from 1 t.s. and up to 3 t.s. were used, designated as DOSM-1 and DOSM-3, respectively.

In accordance with the graduation certificate, the smallest division of the indicator scale (0.01 mm) corresponds to 1.603 kgf for DOSM-1, or 1 mm of indicator compression equals 555.5 kgf. To obtain experimental points of the “force-strain” characteristic, the value of the spring deformation was assigned according to indicator 11. The static load was created by the screw 7, which compresses the dynamometer bracket through the stand 12 and the plate 10, consequently deforming the spring 13. The value of the initial compression (deformation) of the spring was set at $f_0 = 0.3$ mm, and then the load and, accordingly, the deformation of the spring was increased in increments of 0.25 mm. The maximum spring deformation was restricted to the value $f_{max} = 2.05$ mm. The choice of the initial spring deformation of 0.3 mm and the step size for changing the deformation of 0.25 mm made it possible to obtain a sufficient number of points of the “force-strain” characteristic for plotting graphs. The same data (except for the table of the geometrical parameters of the spring) were used in preparing the algorithm to solve the problem of determin-

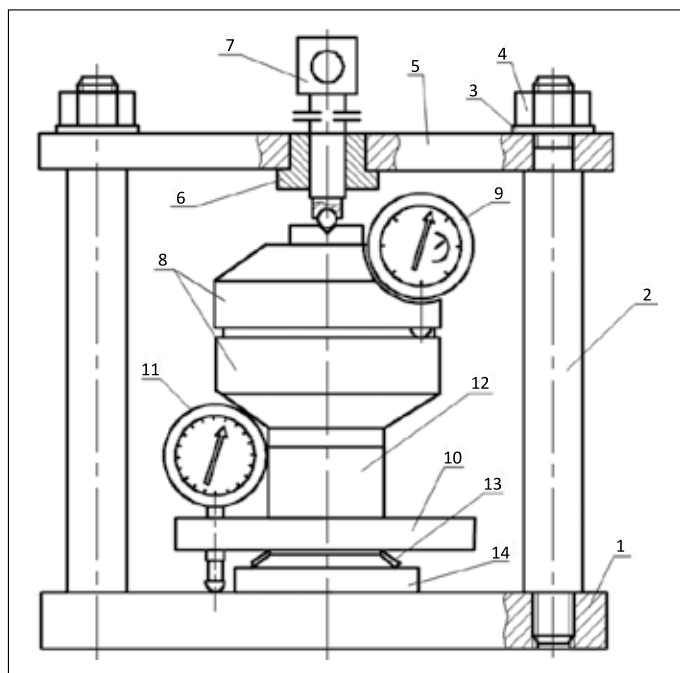


Figure 1. Device for measuring the “force-strain” characteristic of Belleville springs

Rysunek 1. Urządzenie do pomiaru charakterystyki “siła–odkształcenie” sprężyn Belleville

ing the magnitude of the static compression force (P , kgf) for given spring deformation values (f , mm).

These characteristics were calculated on a computer, taking into account the variation in the thickness of the spring material from 1.8 mm to 2.3 mm (Figure 2).

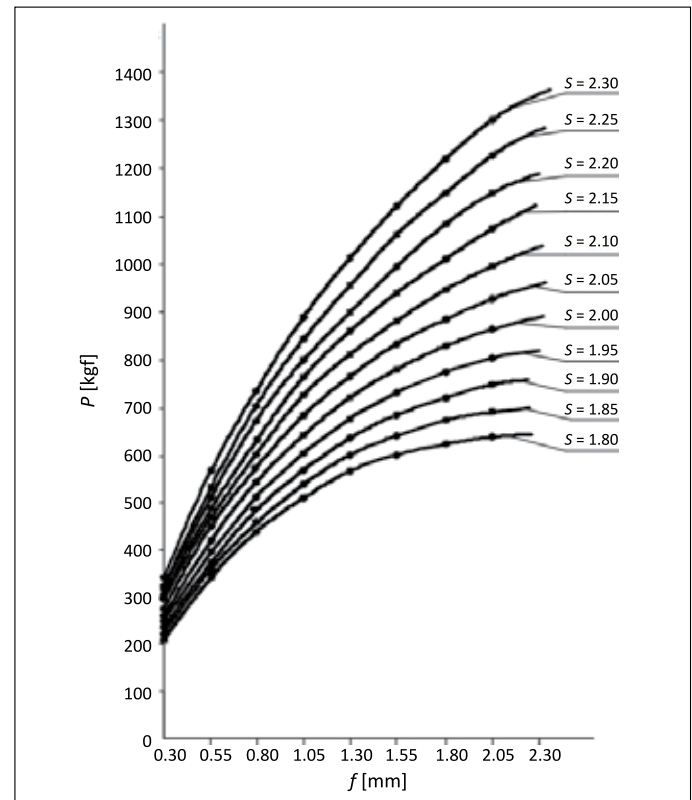


Figure 2. Dependence of the design characteristics “force-strain” on the thickness S [mm] of the spring at a height $H = 4.5$ mm

Rysunek 2. Zależność charakterystyki obliczeniowej “siła–odkształcenie” od grubości S [mm] sprężyny na wysokości $H = 4,5$ mm

The spring drawing shows two points of the “force-strain” characteristic: a force of 480 kgf at a deformation of 1.3 mm (height 3.2 mm) and a force of 800 kgf at a deformation of 1.8 mm (height 2.7 mm). These points correspond to the mounting and operating values of the spring compression in the gate valve (Megawati et al., 2012).

The measurement of the spring compression force at a given deformation was repeated five times for each spring, conducting five parallel experiments. During the study, the springs were divided into groups. Within one group, the springs differed in height by no more than $\Delta H = 0.2$ mm, and in material thickness by no more than $\Delta S = 0.05$ mm.

The measurement of the static compression force for each value of the deformation was made for each group of similarly sized springs. Then, the arithmetic mean value of the static force for each strain was determined, and from these data, the experimental “force-strain” characteristics were built for

each group of springs. The measurement data of the residual deformation value and the frequency of each residual deformation value within the selected 0.2 mm interval are shown in Table 1.

Table 1. Empirical distribution of residual deformation of disc springs

Tabela 1. Empiryczny rozkład odkształceń resztkowych sprężyn talerzowych

Permanent deformation interval f_{ocr} [mm]		Middle	Purity
from	before	f_{ocr} [mm]	n
0.6	0.8	0.7	4
0.8	1.0	0.9	10
1.0	1.2	1.1	12
1.2	1.4	1.3	6
1.4	1.6	1.5	4

Based on the data presented in Table 1, an empirical curve depicting the distribution of residual deformation of disc springs was constructed (Figure 3).

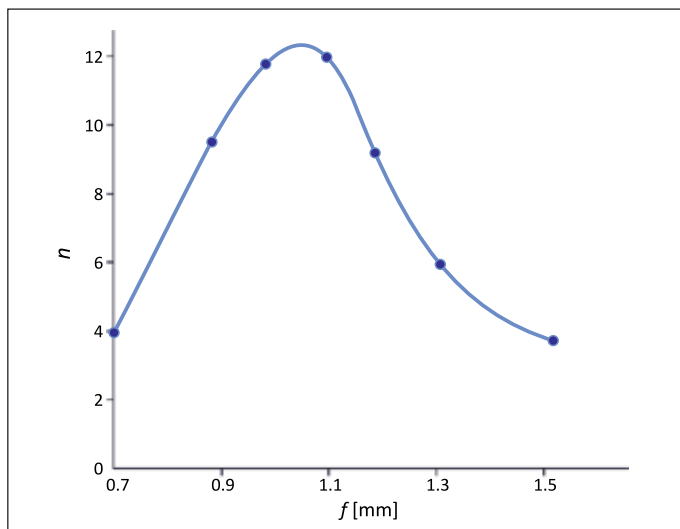


Figure 3. Empirical distribution of residual deformation of a Belleville spring after captivity

Rysunek 3. Empiryczny rozkład odkształceń resztkowych sprężyn Belleville po zamontowaniu

From Figure 3 it follows that the most probable range for the residual deformation of springs made of steel 65G falls between 0.8 and 1.2 mm (for 80% of springs). Consequently, this leads to a significant reduction in the height of the spring and a variation in the size of the height. For these reasons, the influence of the height of the spring on its elastic properties was investigated. Thus, the influence of the spring height on its elastic properties has been established with high reliability. The residual deformation after captivity reduced the height of the spring in the range of 3.7 to 4.2 mm, which, accordingly,

reduced the elastic deformation of the spring by 0.8 to 0.3 mm during its installation and, as a result, the pressing force of the seat to the gate.

At the same time, as shown above, the reduction in spring height to the indicated values led to a decrease in spring stiffness by 30–10%.

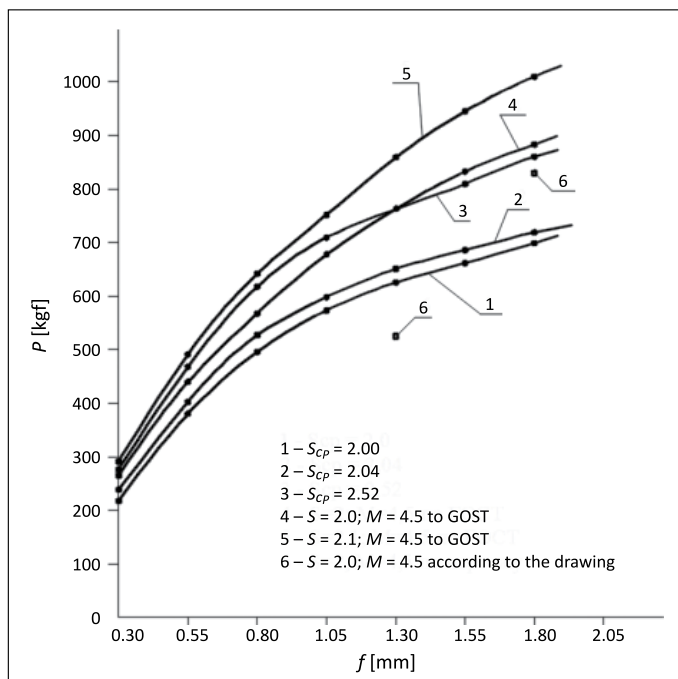
Table 2 shows the data on the total change in the height of the springs, the force (pressure) of applied to press the seat against the gate valve. It follows from Table 2 that only the springs with a height of 4.3 mm are close in their parameters to those calculated according to GOST standard and can quite reliably seal the shut-off valve assembly at low pressures ranging from 3 to 5 MPa. It should also be noted that the changes in the “force-deformation” relationship at different deformations correspond to the variations observed in the calculated characteristics.

The difference between the experimental “force-deformation” characteristics and those calculated according to GOST standard can be attributed to the design differences between the springs used and those conforming to the GOST standard. Further research is needed to determine the correction factors for GOST formulas to enable their application in calculating the stiffness and stresses in Belleville springs of direct-flow valves. The impact of spring material thickness s_{cp} on its characteristic “force-deformation” is detailed. It was found that the change in thickness s_{cp} from 2.0 mm to 2.1 mm, with close values of springs height $H_{cp} = 4.25 \dots 4.30$ mm), resulted in an 18 to 20% increase in spring stiffness. On average, a 0.01 mm increase in spring thickness corresponds to about a 2% increase in spring constant. Similar results were obtained when analyzing the characteristics in Figure 4. Comparison of curves 1 and 3 shows that an increase in the spring thickness from 1.9 mm to 2.06 mm at $H_{cp} = 3.90\text{--}3.95$ mm leads to a 32 to 38% increase in stiffness, which corresponds to an increase in stiffness by 2.0 to 2.4% for every 0.01 mm increase in spring thickness.

A comparison of curves 2 and 4 in Figure 4 also shows that a change in spring material thickness by 0.01 mm corresponds to a change in the spring stiffness by 2%. The change in spring stiffness by 1.5 to 2.0% for every 0.01 mm of thickness is also confirmed by the experimental data on curves 2.4 and 5.0 of in Figure 4. An analysis of the design characteristics in the range of spring thicknesses from 1.8 mm to 2.3 mm shows that the stiffness of the springs increases with increasing thickness according to a pattern similar to the experimental characteristics. An increase in spring thickness by 0.01 mm causes an increase in spring stiffness by approximately 2%. At the same time, it should be noted that the absolute value of the spring stiffness according to the calculated characteristics is 10–20% higher than that of the experimental data, a discrepancy attributed to

Table 2. Influence of the height of the spring on the force and pressure of pressing the seat to the gate**Tabela 2.** Wpływ wysokości sprężyny na siłę i docisk gniazda do zasuwy

You Spring height H_{cf}	Spring thickness S_{cf}	Mounting deformation of the spring f_m	Assembly spring compression force R_m	Mounting pressure of the saddle on the gate R_m	Working deformation of the spring f_p	The working force of compression of the spring R_p	Working pressure of the saddle on the gate from the action of the spring P_p
[mm]	[mm]	[mm]	[kgf]	[MPa]	[mm]	[kgf]	[MPa]
3.70...3.80	1.95...2.00	0.50...0.60	260...290	1.60...1.80	1.00...1.10	400...420	2.50...2.65
4.10	2.0	0.9	495	3.1	1.4	595	3.80
4.30	2.0	1.1	570	3.6	1.6	645	4.10
4.50	2.0	1.3	740	4.7	1.8	850	5.40
4.50	2.0	1.3	480	3.0	1.8	800	5.05

**Figure 4.** Dependence of the characteristic “force-strain” on the thickness s_{cp} [mm] of the spring at height $H_{cp} = 4.27 + 0.01$ mm**Rysunek 4.** Zależność charakterystyki “siła-odkształcenie” od grubości s_{cp} [mm] sprężyny na wysokości $H_{cp} = 4,27 + 0,01$ mm

design differences between the springs used and those meeting the GOST standard. In accordance with GOST 3057, Belleville springs manufactured according to the second accuracy group can have maximum force deviations of $\pm 10\%$, while according to the third accuracy group – of $\pm 20\%$. This means that the spring thickness tolerance must be ± 0.05 mm for springs of the second accuracy group and ± 0.01 mm for springs of the third accuracy group.

Considering that the experimental data indicates that spring stiffness is 10 to 15% less than the calculated data according to GOST, it is advisable to choose spring material thickness within the following limits – $S = 2^{+0.15}_{-0.05}$ mm. In this case, most springs will, in terms of their stiffness, closely approximate the calculated data for a spring with nominal dimensions, i.e. $S = 2$ mm and $H = 4.5$ mm. For a spring with a height of $H = 4.5^{(\pm 0.24)}$ mm and $S = 2^{+0.15}_{-0.05}$, it is necessary to include a “force-strain” characteristic graph in the drawing. This graph should indicate the force of 650^{+120}_{-50} kgf at an installation deformation of 1.3 mm ($H = 3.2$ mm) and the force of 750^{+120}_{-50} kgf for a maximum working deformation of 18 mm ($H = 2.7$ mm). The results of the hardness and depth of the hardened layer are shown in Table 3.

Table 3. The results of hardness measurements on the PMT-3 device (load 100 g) and the depth of the hardened layer**Tabela 3.** Wyniki pomiarów twardości przeprowadzonych na urządzeniu PMT-3 (obciążenie 100 g) i głębokość utwardzonej warstwy

No. samples	Hardened layer								Base metal		
	h	$3/2 h$	l_g	H_g	l_{deep}	l_g	H_D	l	l_g	H_g	note
1	18	34	10.54	1850	44	13.64	1100	98	30.38	206	3 8X2 MUA
2	18	27	8.37	2900	thirty	9.30	2290	94	29.14	221	40
3				2000							40 X
4	19	42	13.02	1100	78	24.18	322	99	30.68	193	3 8X2 MUA
5	18	56	17.36	642	58	17.98	572	94	29.14	221	40 X
6	20	42	13.02	1100	69	21.39	420	83	25.73	274	40
7	20	–	–	1800	–	–	1100	–	–	206	3 8X2 MUA
8	18	33	10.23	1850	53	16.43	724	76	23.56	350	40X
9	17	36	10.16	1530	68	21.08	420	96	29.76	206	40
10	15	46	14.26	946	54	16.74	642	69	21.39	250	3 8X2 MUA
11	20	54	16.74	642	68	21.08	420	88	27.28	254	40X
12	20	51	15.81	724	48	14.88	824	88	27.28	254	40

Samples were made from standard grades of steel 40, 40Kh 38Kh2MYuA, and subjected to hardening using the methods under consideration. A study was made of the hardness and depth of the hardened layer has been conducted.

Conclusions

In light of the research regarding the impact of geometric parameters and heat treatment technology on the elastic characteristics of a Belleville springs in direct-flow valves, the following conclusions can be drawn:

1. The relationship between spring compression force, as well as its deformation, and the geometric parameters of disc springs has been established, and a comparison of experimental and theoretical dependences has been carried out. It has been confirmed that the residual deformation of Belleville springs after captivity has a negative effect on the tightness of the shut-off valve assembly.
2. The influence of various technological processes and thermal treatment methods on elastic properties of disc springs has been studied. Practical recommendations for improving the technological process of thermal treatment of Belleville springs have been proposed, and further research tasks and the implementation of the obtained results have been identified. Search work has been carried out to improve the technology of hardening processing of parts of the shut-off unit (gate and seat) of direct-flow valves.
3. The possibility of using accelerated nitrocarburizing in a triethanolamine medium with induction heating by high-frequency currents at a temperature range of 950°C for boriding and boro-chroming has been established.
4. Samples were made from standard steel grades 40, 40Kh and 38Kh2MYuA, subjected to hardening using the methods under consideration, and a study of the hardness, depth and microstructure of the hardened layer has been conducted. Research in this direction should be continued in order to study the tribological characteristics (friction coefficient and wear resistance) of hardened parts.

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