Development of A High Stiffness Linear Compression Spring

Jinfei Huang*, Hangbin Zhang, Wanglin Lin, Xinze Zhao
Zhejiang light industrial products inspection and research institute, Hangzhou, Zhejiang, 310000, China

*Corresponding author’s e-mail: hjf_fytest@163.com
* Corresponding author: baihu2007@aliyun.com

Abstract: This paper summarizes the whole process of design, trial-manufacture, improvement and final design of the spring, which is the core part of the shock absorption device for the surface layer of synthetic materials in the standard GB 36246-2018 “Surface layer sports ground for primary and middle schools”. The successful development of this key part fills the blank of spring deformation parts in domestic testing industry, and can be used in other fields.

1. Background
Plastic track is also known as all-weather track, it is composed of polyurethane prepolymer, mixed polyether, waste tire rubber, EPDM rubber or PU particles, pigments, additives and fillers. Plastic runway has the characteristics of good flatness, high compressive strength, appropriate hardness and elasticity, and stable physical performance. The plastic track is conducive to the performance of speed and technology, and can effectively improve performance, but also can reduce the risk of sports injury. The plastic track is made of polyurethane rubber and other materials, which is recognized as the best all-weather outdoor playground floor material in the world. Plastic track has a certain flexibility and color, but also uv resistance and aging resistance performance.

In recent years, China has rapidly developed sports undertakings, undertaken all kinds of large-scale international sports events, and carried out the construction of all kinds of sports venues. The General Administration of Sport of China and the Ministry of Education issued the Notice on The Opinions on Deepening The Integration of Sport education and Promoting the Healthy Development of Adolescents ([2020] No. 1 Issued by the General Administration of Sport), which proposed to comprehensively improve the quality education for adolescents. The paper puts forward that "physical education subjects should be included in the scope of academic proficiency tests for junior and senior high schools and included in the scoring subjects for senior high schools". The paper clearly points out that the plastic track is the infrastructure of talent cultivation. The new synthetic plastic material is used in many stadiums and runways. In order to ensure the normal holding of sports events and normal sports teaching in schools, it is necessary to carry out various tests on the newly built, rebuilt or constructed plastic track and ensure that the plastic track meets the standards and requirements.

“Synthetic Material Surface Sports Venues for Primary and Secondary Schools” is a mandatory national standard on plastic running tracks drafted by the Ministry of Education and participated by dozens of scientific research institutes and testing institutions. The standard went into effect on November 1, 2018, after more than two years of revision. The standard refers to the requirements for the detection method of impact absorption of synthetic materials surface layer and the requirements for the detection device. The key component of the equipment is the compression spring, which can measure the maximum impact absorption force. This spring is a non-standard spring not available on
the market. So we decided to develop and design the spring ourselves.

2. Design and Manufacture of Spring Basis
The standard GB 36246-2018 “Sports Fields for Surface Layers of Synthetic Materials in Primary and Secondary Schools” puts forward the structure of the detection device for surface layers of synthetic materials impact absorption and the technical requirements of spiral springs. The outer diameter of the spring is 69mm, and the upper surface needs to be hardened. The linear spring stiffness is 2000N/mm. And the forces range is from 0.1kN to 7.5kN. The spring may be wound by three or more coaxial coils. The spring can be mill from a steel block. And the ends of each coil should be fixed together.

3. The Manufacturing Process of A Spring
a) The First Trial Production
Spring parameters are assumed according to GB 36246-2018 standard content, equipment structure guidance diagram and test process description. The spring form is spiral cylinder compression spring, the material is 65Mn. Calculation formula of elastic coefficient of cylindrical spring:

\[ k = \frac{G \times d^4}{8 \times N_c \times D_{in}} \]

The diameter of the spring can be calculated by the spring’s elasticity coefficient K. Then according to the diameter of the spring, you can calculate the diameter of the spring hole and the spring pitch. The spring shape structure is drew with 3D software.

The wire diameter of the spring is 10mm and the pitch of the spring is 18mm. After the spring on both ends of the molding process. Finally, the spring is tested for pressure. The test results show that the elastic stiffness of the actual spring is 1200N/mm. This figure does not correspond with reality. So
the first trial production failed.

b) The Second Trial Production

After looking up a lot of information about spring, we found that the linearity of rectangular section spring is obviously better than spiral cylindrical spring. Rectangular spring calculation formula.

Spring diameter ratio——c [c=D/d]
Line width——b [mm, in]
Wire diameter——d [mm, in]
Center diameter——D [mm, in]
The spring load——F [N, lb]
Modulus of shear elasticity——G [MPa, psi]
High line——h [mm, in]
Spring coefficient——k [N/mm, lb/in]
Curve correction factor——Ks
Free length——L0 [mm, in]
Solid height——LS [mm, in]
Effective number of turns——n
Pitch——p [mm, in]
Spring deformation——s [mm, in]
Shape factor——φ
Torsional stress of spring material——t [MPa, psi]

65Mn is selected as the spring material. Through calculation, the rectangular section size of the spring is 8.5mm×7mm, the spring pitch is 16mm, the outside diameter of the spring is 69mm, and the spring shape is a single-head spiral spring. However, most manufacturers are unable to make springs with this parameter due to equipment reasons. Finally, we decided to process the spring through milling. So we through the four axis machining center will be processed out of the spring, and then the processed spring heat treatment. Finally, we pressure tested the spring and found that the spring's elasticity coefficient was only 1400N/mm. This spring does not meet the test requirements. The second trial failed.

c) The Third Trial Production

After the previous failures, we came up with a new plan. We replaced the original single-wire spring with multi-wire spring. In this way, each single-wire spring only needs to achieve one third of the total performance. The wire diameter of the single-wire spring is 7mm×8mm, the spring pitch is 48mm, and the spring outer diameter is 69mm.
Figure 3 — Single wire spring after processing and forming

By means of wire cutting, three single-wire spring are processed to ensure that each single-wire spring has the same end face size. Three single-wire spring and end cover are bonded by resin adhesive, and a multi-wire spring is formed after bonding.

Figure 4 — Adhesion of the multi - wire spring

Then we do a pressure test on the spring. The results were not what had been expected. The spring is not linear or rigid. The third trial production failed.

d) The Forth Trial Production

We continue to summarize the previous failure results and draw the following conclusions.

1) Through the selection of high quality spring materials, to improve the yield strength of the spring.

2) Adopt multi - line spring system scheme, through the whole milling processing method to process the spring.

3) Before the spring processing, the finite element software is needed to analyze the force of the spring.

Finite Element Analysis (FEA, Finite Element Analysis) is to use mathematical approximation method to simulate the real physical system (geometry and loading condition). In addition, simple and interacting elements, namely elements, can be used to approximate the real system of infinite unknowns with a finite number of unknowns. Finite element analysis is to replace complex problems with simpler ones and then solve them. It considers the solution domain to be composed of many small interconnected subdomains called finite elements, assumes an appropriate (simpler) approximate solution for each element, and then deduces the solution to the problem by solving the general conditions (such as the equilibrium conditions of the structure) of this domain.

ANSYS finite element analysis software is used to analyze the 3D model. After analyzing and modifying the model parameters, the model is processed.

Finally, we set the material of the spring as 60Si2Cr4A. The finite element analysis process of the spring is shown in the figure below:
Figure 5 — The deformation effect of the spring at a pressure of 2000N

Figure 6 — The deformation effect of the spring at a pressure of 4000N

Figure 7 — The deformation effect of the spring at a pressure of 6000N
Figure 8 — The deformation effect of the spring at a pressure of 7500N

1) Original model parameters (spring bore is 44.5mm)

Function 1:
F1=2000N, U1=0.92992mm  K=2000/0.92992=2151N/mm
Maximum Equivalent Stress σv =201.6MPa (von Mises stress)

Function 2:
F2=4000N, U2=1.8599mm  K=4000/1.8599=2151N/mm
Maximum Equivalent Stress σv =403.2MPa (von Mises stress)

Function 3:
F3=6000N, U3=2.7898mm  K=6000/2.7898=2151N/mm
Maximum Equivalent Stress σv =604.8MPa (von Mises stress)

Function 4:
F4=7500N, U4=3.4872mm  K=7500/3.4872=2151N/mm
Maximum Equivalent Stress σv =756.0MPa (von Mises stress)

2) Spring bore is 44.7mm

Function 1:
F1=2000N, U1=0.9493mm  K=2000/0.9493=2107N/mm
Maximum Equivalent Stress σv =207.0MPa (von Mises stress)

Function 2:
F2=4000N, U2=1.8987mm  K=4000/1.8987=2107N/mm
Maximum Equivalent Stress σv =414.0MPa (von Mises stress)

Function 3:
F3=6000N, U3=2.8480mm  K=6000/2.8480=2107N/mm
Maximum Equivalent Stress σv =620.9MPa (von Mises stress)

Function 4:
F4=7500N, U4=3.5599mm  K=7500/3.5599=2107N/mm
Maximum Equivalent Stress σv =776.2MPa (von Mises stress)

3) Spring bore is 45.2mm

Function 1:
F1=2000N, Top Surface U1=0.99451mm  K=2000/0.99451=2011N/mm
Maximum Equivalent Stress σv =205.1MPa (von Mises stress)

Function 2:
F2=4000N, Top Surface U2=1.8987mm  K=4000/1.8987=2011N/mm
Maximum Equivalent Stress σv =414.0MPa (von Mises stress)

Function 3:
F3=6000N, Top Surface U3=2.8480mm  K=6000/2.8480=2011N/mm
Maximum Equivalent Stress σv =620.9MPa (von Mises stress)
Function 4:
F4=7500N, Top Surface U4=3.7294mm  K=7500/3.7294=2011N/mm
Maximum Equivalent Stress σv =769.1MPa (von Mises stress)

4) Spring bore is 45.3mm

Function 1:
F1=2000N, Top Surface U1=1.0027mm  K=2000/1.0027=1994.6N/mm
Maximum Equivalent Stress σv =207.7MPa (von Mises stress)

Function 2:
F2=4000N, Top Surface U2=2.0055mm  K=4000/2.0055=1994.5N/mm
Maximum Equivalent Stress σv =415.4MPa (von Mises stress)

Function 3:
F3=6000N, Top Surface U3=3.0082mm  K=6000/3.0082=1994.5N/mm
Maximum Equivalent Stress σv =623.0MPa (von Mises stress)

Function 4:
F4=7500N, Top Surface U4=3.7602mm  K=7500/3.7294=1994.6N/mm
Maximum Equivalent Stress σv =778.8MPa (von Mises stress)

Safety Factor: 1570/778.8=2.016

Figure 9 — Sample with spring inner meridian of 45.3mm

Then the spring is tested. The pressure range is between 1000N and 7000N, and the spring elasticity coefficient is 1400N/mm. The elasticity is still small compared to the expected value. However, no plastic deformation occurred during the whole test. This indicates that the spring has basically met the requirements of the conditions, but it still needs to be further refined.

e) The Fifth Trial Production

This time, we adjust the spring parameters again. The coefficient on which the spring parameters are adjusted is the ratio of the spring elasticity coefficient of the fourth test to that of the required spring. After adjusting the spring parameters, the finite element analysis of the spring is carried out again.
Figure 10 — The amount of deformation of the adjusted spring under 2000N force

Figure 11 — The amount of deformation of the adjusted spring under 4000N force

Figure 12 — The amount of deformation of the adjusted spring under 6000N force
Figure 13 — The amount of deformation of the adjusted spring under 7500N force

Adjusted spring parameters:

Function 1:
\[ F_1=2000N, \quad U_1=0.73442mm \quad K=\frac{2000}{0.73442}=2723.24N/mm \quad K_{sj}=70\%K=1906.3 \]
Maximum Equivalent Stress \( \sigma_v =169.8\text{MPa}(\text{von Mises stress}) \)

Function 2:
\[ F_2=4000N, \quad U_2=1.46884mm \quad K=\frac{4000}{1.46884}=2723.24N/mm \]
Maximum Equivalent Stress \( \sigma_v =339.7\text{MPa}(\text{von Mises stress}) \)

Function 3:
\[ F_3=6000N, \quad U_3=2.20326mm \quad K=\frac{6000}{2.20326}=2723.24N/mm \]
Maximum Equivalent Stress \( \sigma_v =509.6\text{MPa}(\text{von Mises stress}) \)

Function 4:
\[ F_4=7500N, \quad U_4=2.75408mm \quad K=\frac{7500}{2.75408}=2723.23N/mm \]
Maximum Equivalent Stress \( \sigma_v =637.0\text{MPa}(\text{von Mises stress}) \)

Through finite element software analysis, the following conclusions can be drawn:

1) The elastic coefficient of the target spring is 2000N/mm. The shrinkage of the target spring at 2000N is 1mm. \( K_{cp}=2000 \)
2) The actual spring elasticity coefficient is 1400N/mm. The actual shrinkage of the spring under force of 1400N is 1mm. \( K_{yp}=1400 \)
3) \( K_{yp}/K_{cp}=1400/2000=0.7 \) The actual spring rigidity is 70% of the target spring rigidity.
4) If the shape, material and process are not changed. Just fine tune the spring size. So the stiffness of the actual spring is going to be the stiffness of the target spring times 70%. \( K_{sj}=70\%K \).

It is recommended to reduce the inside diameter of the spring and increase the outside diameter. In this way, the performance parameters of the spring can be adjusted by means of finishing.

There may be performance differences for mass-produced springs. So every spring that comes out of mass production needs to be tested. Then adjust the production equipment through the spring test results.

We processed two spring samples in the above way. The two spring samples were tested. The test results show that the elasticity coefficient of one spring is 2100N/mm, and that of the other spring is 2150N/mm. After that, we finished the two respectively. The inner hole of one spring was enlarged by 0.1mm, and the inner hole of the other spring by 0.15mm. Then the two springs were tested, and the elastic coefficients of the two springs were 2020N/mm and 2040N/mm, respectively. The spring's elastic coefficient requirement (2000N/mm±60N/mm) has been met. Both springs meet the standard requirements perfectly.
4. Summarize
Through the interpretation of the spring requirements in the standard of GB 36246-2018 “Sports Field of Surface Layer of Synthetic Materials in Primary and Secondary Schools”, as well as the change of process, material selection and improvement of heat treatment method, a spring meeting the standard requirements has been successfully developed. Fully it has filled the domestic market in this area of the gap.

5. Funds to Support
This research is supported by the Research Fund of Zhejiang Provincial Administration of Market Supervision (Serial number20190116).

Reference
[1] China Standardization administration (2018). GB 36246:2018, Synthetic material surface sports grounds for primary and secondary schools.
http://www.gb688.cn/bzgk/gb/newGbInfo?hcno=4582A6129CD00E3D737BE27C49328062.
[2] Wen Bangchun. Mechanical Design Manual (2010) 5th edition Beijing: Machinery Industry Press.
[3] Zhang Yinghui, Liu Huihang, Wang Decheng (2017) Spring Manual, 3rd edition Beijing: Machinery Industry Press.
[4] Jiang Minsheng (2019) ANSYS Workbench 19.0 Basic Introduction and Engineering Practice (with instructional video): People's Posts and Telecommunications Press.
[5] Wang Shilong, Zhou Jie, Li Xiaoyong (2011) Multiple coil spring: Science Press.
[6] Qin Datong, Xie Liyang (2013) Spring design-now mechanical design manual-single edition: Chemical Industry Press.