Optimization Design of Hydraulic Valve Block and Its Internal Flow Channel Based on Additive Manufacturing

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Abstract: Hydraulic valve block is an important part of the hydraulic system. The traditional hydraulic valve block is made by turning and milling, drilling and boring, which leads to many right-angle bending and closed cavity structure of process holes in its internal flow channel, seriously affecting the flow performance of oil. Based on the new design space provided by additive manufacturing technology, the internal hydraulic flow channel of valve block is optimized by using B-spline curve. Computational fluid dynamics analysis is carried out on the hydraulic flow channel to determine the optimal flow channel structure with the smallest pressure drop. The weight reduction of hydraulic valve block is carried out through topology optimization. According to the results of topology optimization, using the method of selective laser melting (SLM), the printing of the hydraulic valve block is completed. The optimized hydraulic channel reduces the pressure loss by 31.4% compared with the traditional hydraulic channel. Compared with the traditional valve block, the hydraulic valve block manufactured by SLM with topology optimization reduces the weight by 33.9%. Therefore, the proposed flow channel optimization and valve block lightweight method provide a new reference for the performance improvement of the internal flow channel of hydraulic valve block and the overall lightweight design of valve block.

Key words: flow channel optimization; B-spline curve; pressure loss; topology optimization; additive manufacturing

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0 Introduction

Hydraulic system is widely used in machinery manufacturing, engineering machinery, military equipment, ships, aerospace and other fields. In recent years, the hydraulic system has been developing in the direction of integration, lightweight, miniaturization, high performance and high reliability, especially in the aerospace field. Hydraulic valve block is usually the concentrated embodiment of the integration of the hydraulic system, and it is an indispensable part of the integrated hydraulic system.

Traditional hydraulic valve blocks are manufactured on forged steel or continuous casting blanks by turning milling, drilling, boring and other processing methods. These manufacturing methods, have complex manufacturing processes and long processing cycles, which are obviously unable to meet the requirements of lightweight, miniaturized, and high-performance hydraulic components in the aerospace field. The emergence of additive manufacturing (AM) technology provides a new method for the design and manufacture of hydraulic valve blocks, especially for aerospace hydraulic valve blocks that are not cost-sensitive and require extremely high weight and performance. Compared with the traditional subtractive manufacturing method, AM is a bottom-up method of material accumulation[1-4], which breaks through the limitations of traditional manufacturing technology and solves the problem of “manufacturing determines design” in product research and de-

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velopment. AM has been widely applied in aerospace, rail transit and medical fields after nearly 30 years of development[5-9].

AM can realize the complex hydraulic flow channel characteristics inside the hydraulic valve block and improve the flow characteristics inside the flow channel. At present, it has been successfully applied in integrated air ducts and connecting pipes of industrial robots as well as complex flow channels inside sound damping devices[10-14]. Advanced semiconductor material lithography (ASML)[15] uses TiGR5 material to print integrated circuits using selective laser melting (SLM) technology, which reduces weight compared to traditional processing methods. Renishaw[16] has produced hydraulic blocks through AM technology, and successfully used them on Airbus A380. Alshare et al.[17] and Diegel et al.[18] designed and printed hydraulic valve blocks based on AM technology. The above research is only on the basis of retaining the internal flow channel of the traditional hydraulic valve block and reducing the excess material of the valve block, which has not optimized the design of the internal flow channel of the hydraulic valve block. Although some scholars used the computational fluid dynamics (CFD) method to optimize the design of right-angle flow channels inside hydraulic manifold blocks[19], they have not made full use of the new design space provided by AM and broken through the limit of traditional hydraulic flow channel design.

On the premise that the internal flow channel of the hydraulic valve block is connected, how to achieve the optimal smooth transition of the flow channel and minimize the pressure loss of the internal flow in the flow channel are the difficulties in optimizing the internal flow channel of the hydraulic valve block. At present, B-spline curves are mostly used to solve path planning and vehicle obstacle avoidance. B-spline curves have not yet been used to optimize the design of internal flow channels in hydraulic valve blocks. The smooth transition property of B-spline curve combined with AM technology provides a new idea for the optimal design of hydraulic flow channel. Topology optimization technology is an effective design method to seek lightweight and high performance in the aerospace field. Therefore, this paper will use B-spline curve to optimize the design of the internal flow channel of the hydraulic valve block, and integrate the additive manufacturing and topology optimization technology to give full play to their respective advantages in completing the optimization design of the hydraulic valve block.

1 Physical Model of Hydraulic Valve Body

This article takes the electromechanical servo valve used in the aerospace field as the research object, and its assembly model is shown in Fig.1. The electromechanical servo valve is composed of a valve block, a low pressure port connector, a high pressure port connector, a valve core, a relief valve, a filter valve and a process plug. When the electromechanical servo valve works, the oil flows from the low-pressure inlet and flows into the filter valve under the pressure of the spool. A part of the oil flows into the spool through the relief valve, and the other part flows out through the high-pressure outlet. The traditional hydraulic valve block flow channel is mainly made by turning and milling, drilling, boring and other ways, causing the hydraulic valve block internal flow channel to be straight hole flow channel. And there is a closed chamber at the right-angle bend. This will inevitably lead to the loss of fluid pressure inside the valve block. In addition, the flow channel manufactured by the traditional machining method also needs to add a process hole on the end face of the valve block, and the valve assembly

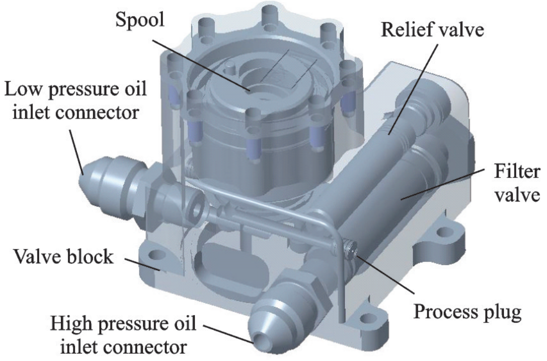


Fig.1 Electromechanical servo valve

needs to install a process plug at the process hole, which increases the risk of oil leakage in the valve.

The internal flow channel structure of the hydraulic valve block is shown in Fig.2. It can be seen from Fig.2 that the valve block has three main flow channels and two craft holes, and the flow channel has a right-angle turn and a closed cavity structure. By adopting AM, the design freedom of the internal flow channel of the valve body will be greatly improved, and the traditionally manufactured straight-hole flow channel structure will be changed. The right-angle turning of the internal flow channel can adopt arc transition to reduce the pressure loss of the flow channel at the turning point. In addition, the internal process holes of the valve block will be removed, the closed cavity will be reduced, and the weight of the valve block will be reduced. Miniaturization and light weight are eternal themes in the aerospace field. For this reason, it is necessary to develop the optimization design of AM hydraulic valve blocks and their internal flow channels.

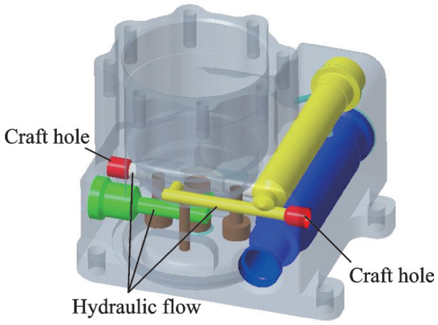


Fig.2　Internal structure diagram of hydraulic valve block

2　Optimization Design of Valve Internal Flow Channel

2.1　Optimal design of typical runner structure

Take the oil return channel connecting the relief valve and the valve core inside the valve block as an example. By additive manufacturing based optimization design, the hydraulic channel structure extracted from the valve block is shown in Fig.3, where A is the oil inlet and B the oil outlet.

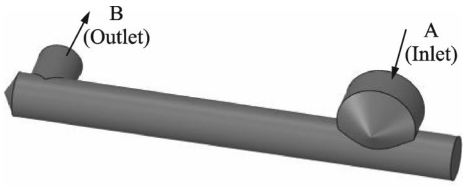


Fig.3　Extracted hydraulic flow channel

AM technology greatly improves the flexibility of hydraulic channel design. For the hydraulic flow channel in Fig.3, the inlet and outlet center positions of the flow channel remain unchanged, and arc transition processing is performed on the right-angle of the flow channel to obtain three flow channel structures, as shown in Fig.4. Because the inlet and outlet center positions are not in the same plane, Type Ⅰ hydraulic inlet position adopts the step type flow channel transition, and the flow channel exit for arc transition processing. By comparison with Fig.3, it can be seen that the sharp angle generated by mechanical processing is optimized into a hemispherical structure at the inlet of Type Ⅱ flow channel, and an arc transition processing is carried out at the outlet of the flow channel. Type Ⅲ flow channel has undergone arc transition treatment at the oil inlet and outlet. Compared with Types I and II, Type Ⅲ flow channel eliminates the step transition and hemispherical transition structure at the oil inlet. Although the above three kinds of flow channels cancel the process hole and closed cavity, when the oil passes through the arc transition of the flow channel, due to the sudden change of the flow direction, it is bound to cause local pressure loss. In order to reduce the pressure loss of the flow channel, the flow channel should be smooth transition to reduce the arc structure. The smoothness of B-spline curve is in line with the requirements of fluid for smooth and streamlined wall surface, so this paper uses B-spline curve to optimize the internal flow channel of

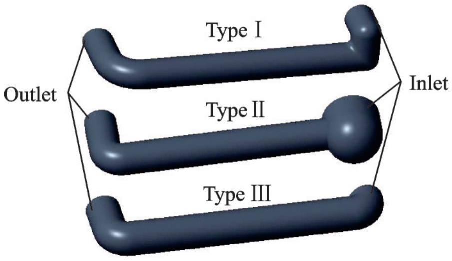


Fig.4　Three hydraulic channel optimization models

valve block.

B-spline curve is a linear combination of B-spline basis functions[20]. That is, given $n+1$ control points ($p_0, p_1, \cdots, p_n$) and a set $\boldsymbol{U}=\{u_0, u_1, \cdots, u_m\}$ ($m=p+n+1$) , a p-degree B-spline curve can be obtained, and the B-spline curve formula is

$$C(u)=\sum_{i=0}^{n} N_{i,p}(u)P_i \tag{1}$$

The set $\boldsymbol{U}$ is called node vector, and $u_0, u_1, \cdots, u_m$ are called nodes, where $u_i \leqslant u_{i+1}(i=0, 1, \cdots, m-1)$. $N_{i,p}(u)$ represents the B-spline basis function and its specific expression is as follows

$$N_{i,0}(u)=\begin{cases}1 & u_i \leqslant u < u_{i+1} \\ 0 & \text{Else}\end{cases} \tag{2}$$

$$N_{i,p}(u)=\frac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u) \tag{3}$$

In this paper, the quadratic B-spline curve is used to draw the curve for the center line of the hydraulic flow channel. Three control points are selected, as shown in Fig.5. The inlet of the flow channel is used as the first control point P_1, the outlet of the flow channel is used as the last control point P_3, and the midpoint P_2 of the main flow channel is selected as the second control point. Extract the three-dimensional coordinates of the three control points for calculation, and the fitted quadratic B-spline hydraulic flow channel center curve is shown in Fig.6.

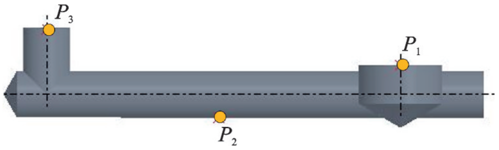


Fig.5 Control point selection

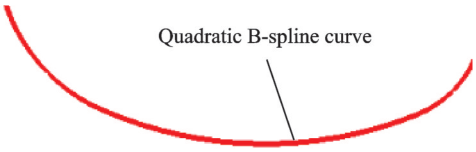


Fig.6 Center curve of quadratic B-spline runner

According to the B-spline curve shown in Fig.6, the three-dimensional model of the flow channel is created as shown in Fig.7. It can be seen that the hydraulic flow channel created by B-spline curve is smoother. Compared with the traditional hydraulic channel model, the smooth connection of the inlet and outlet of the optimized hydraulic channel is more conducive to the oil flow and reduce the oil pressure loss of oil along the channel.

Fig.7 Three-dimensional model of hydraulic flow channel based on B-spline curve

2.2 Numerical simulation of typical hydraulic flow channel

In order to further analyze the flow characteristics of oil in the flow channel, the ANSYS FLUENT software is used to simulate the traditional flow channel of the valve block, Types Ⅰ, Ⅱ, and Ⅲ, and the flow path created by the B-spline curve.

The oil flow inside the flow channel of the hydraulic valve block can be considered as an incompressible three-dimensional unsteady flow. When the oil flows in the flow channel of the hydraulic valve block, the fluid flows through a right angle or the direction of the flow channel changes in most cases. Therefore, this paper chooses the turbulence model for simulation calculation.

Import the three-dimensional model of hydraulic flow channel established in Cero software into the ANSYS FLUENT software, and then perform simulation pre-processing. The No.15 aviation hydraulic oil is selected as the hydraulic oil. The density is 839.3 kg/m^3 and the viscosity is 0.011 6 kg/(m·s) at 40 ℃. The inlet of the flow channel is defined as a pressure-inlet, and the inlet pressure is 21.5 MPa. The outlet of the flow channel is defined as a velocity-inlet, and the inlet speed is set to -3.395 m/s. Choose k-ε turbulence model and SIMPLE algorithm to numerically solve the flow field inside the flow channel.

To simulate the flow field of the above-mentioned flow channel, the pressure cloud diagram and velocity vector cloud diagram obtained are shown in Fig.8 and Fig.9, respectively.

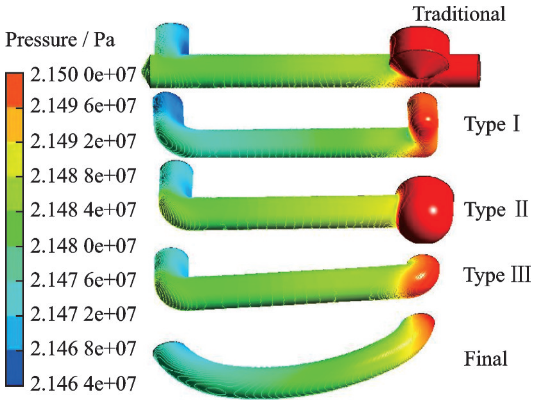


Fig.8 Pressure cloud diagram of different hydraulic flow channels

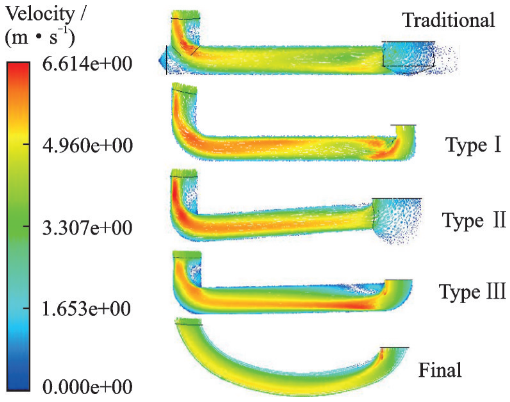


Fig.9 Vector image of plane velocity of different hydraulic channels

Fig.8 shows the pressure cloud diagrams of five different hydraulic channels. It can be seen from Fig.8 that at the entrances of the traditional hydraulic flow channel, Types Ⅰ, Ⅱ, and Ⅲ hydraulic flow channels, when the oil flows through the right-angle turn, the closed cavity, and the small diameter arc transition, a large pressure loss is generated. At the entrance of the traditional hydraulic flow channel, there is a right-angle turning and a closed cavity structure at the same time, so the oil pressure here is relatively large, resulting in a relatively large pressure drop. Compared with the traditional hydraulic flow channel, Type Ⅰ hydraulic flow channel has cancelled the closed cavity structure produced by machining at the oil inlet, but the oil flow direction in the space at the inlet of Type Ⅰ hydraulic flow channel has been changed twice, which is the cause of greater pressure. Type Ⅱ hydraulic flow channel also has a right-angle turning structure at the entrance, and at the same time, it has a hemispherical closed structure, which also generates greater pressure. Type Ⅲ hydraulic flow channel has a small arc transition structure at the entrance, and the change of the oil direction will cause more pressure on the outermost side of the arc transition. Therefore, the arc transition structure with a smaller diameter will also cause the oil inlet pressure loss. It can be seen from Fig.8 that the overall pressure transition of the smooth transition channel created by the B-spline is relatively natural. At the entrance of the channel, the pressure on the outermost side of the channel gradually decreases due to the slow change of the oil direction. Compared with the traditional hydraulic flow channel, the overall pressure distribution of the flow channel created by the B-spline curve is more uniform.

Fig.9 shows vector cloud diagrams of the plane velocity at the center of different flow channels. It can be seen from Fig.9 that due to the oil viscosity, the oil flowing along the inner wall of the flow channel is subject to the frictional resistance from the inner wall of the flow channel, which causes the oil velocity at the inner wall of the flow channel to be lower than that at the center of the flow channel. For the traditional hydraulic flow channel, there are a right-angle steering and closed cavity structure at the oil inlet. When the oil enters with a certain pressure, a part of the oil flows along the main flow channel to the outlet, and another part of the oil flows to the closed cavity. The oil flowing to the closed cavity generates a vortex at the end of the cavity, resulting in irregular rotation, collision and backflow movement of the liquid flow, which consumes the fluid energy and causes the pressure loss of the fluid. Also at the exit of the traditional hydraulic flow channel, the liquid flow also produces vortex phenomenon at the inner side of the right-angle turning and the sharp corner of the closed cavity. After the oil flows into the inlet of Type Ⅰ channel, it makes two right-angle turns in space. After the oil enters the main channel, its speed suddenly increases due to the existence of a vertical right-angle structure at the inlet. After the oil flows into the inlet of Type Ⅱ hydraulic channel, a part of the oil flows to the main channel, and another part of the oil flows to the spherical closed cavity, and produces vortex phenomenon. Compared with Type Ⅱ hydraulic flow channel, Type Ⅲ hydraulic flow channel does not have a closed cavity, but has a right-angle structure with a circular arc transition. Type Ⅲ hydraulic flow channel also has vortex phenomenon at the inmost part of the arc transition of the oil inlet and outlet. In the hydraulic flow channel created by B-spline, the oil flow velocity is relatively smooth and stable, and there is no great change, so the fluid in the flow channel does not appear vortex phenomenon.

Through the above analysis, it can be known that the right-angle turning of the flow channel and the closed cavity structure are the main reasons for the pressure loss and vortex phenomenon. When the oil flows through the turning point of the flow channel, the direction and velocity of the oil change suddenly, and the oil produces vortex at the inside of the turning point of the flow channel, which causes the collision and severe friction between the oil and the wall surface of the flow passage, thus resulting in the loss of oil pressure. In addition, the movement disturbance of the main flow caused by the vortex backflow in the enclosed cavity is also the cause of the pressure loss. The hydraulic flow channel created by the B-spline curve avoids the flow channel turning at right-angles and the closed cavity, the fluid pressure distribution is more uniform, there is no vortex phenomenon, and the flow rate is more stable.

Table 1 shows the specific results of the pressure loss of different hydraulic channels. It can be seen from Table 1 that compared with the traditional hydraulic channel, the pressure losses of Type Ⅰ and Type Ⅲ hydraulic channels increase by 12.2% and 1.9%, respectively, while the pressure loss of Type Ⅱ hydraulic channel is reduced by 10.7%. Compared with the traditional hydraulic flow channel structure, Type I hydraulic flow channel reduces the diameter of the flow channel at the inlet, but adds a right-angle transition structure, which leads to an increase in pressure loss. Compared with Type Ⅲ hydraulic channel, only the diameter at the inlet of the runner is different, but the pressure loss is reduced by 10.7% than the traditional hydraulic channel. From the above analysis, it can be seen that in addition to the right-angle steering and the closed cavity structure, the inlet diameter is also the main cause of pressure loss. Finally, compared with the traditional hydraulic flow channel, the pressure loss of the optimized flow channel with B-spline curve is reduced by 31.4%. It can be seen that the hydraulic flow channel created by using B-spline curve can reduce the pressure loss in the process of oil flow and improve the oil flow efficiency.

Table 1 Comparison results of pressure loss of different hydraulic channels

Hydraulic channel type	Inlet pressure / MPa	Outlet pressure / MPa	Pressure loss / MPa	Percentage of pressure loss compared to the traditional channel /%
Traditional	21.5	21.473 887	0.026 113	
Type Ⅰ	21.5	21.470 714	0.029 286	+12.2
Type Ⅱ	21.5	21.476 668	0.023 332	−10.7
Type Ⅲ	21.5	21.473 396	0.026 604	+1.9
Final	21.5	21.482 094	0.017 906	−31.4

3 Lightweight Valve Block

3.1 Valve block topology optimization

Taking the hydraulic valve block as the optimization object, the static structural and topology optimization modules in AnsysWorkbench19.0 software are used for topology optimization simulation. The smaller the density value in the topology optimization module, the smaller the contribution to the structure, and the larger the density value, the greater the contribution to the structure. Generally, when the density value is in the interval (0, 0.4), the material unit will be removed. When the density value is in the interval (0.6, 1), the material element remains. The material element with the density value in the interval (0.4, 0.6) is the new boundary of the optimized part. The simulation result of topology optimization is shown in Fig.10.

In Fig.10, the material around the flow channel of the hydraulic valve block has been removed, so according to the topology optimization results as a guide, the hydraulic valve block is reconstructed in three dimensions. When rebuilding the valve block, the wall thickness of the valve body should not be less than 2 mm required by the valve body design, and the wall thickness of the flow channel should not be less than 1 mm required by the design. At the same time, considering the constraints of AM, the number of supports is reduced, and a self-supporting structure is designed where it is difficult to remove the supports. The model design tries to avoid the inclination angle of the structure greater than 45°. Taking into account the problem of additive manufacturing forming, the arc transition treatment is carried out at the edges and corners of the structure. Finally, according to the topology optimization results and AM constraint rules, the valve block optimization design is completed. The three-dimensional model comparison of the hydraulic valve block before and after optimization is shown in Fig.11.

Figs.11(a) and (b) are the traditional models of the hydraulic valve block, and Figs.11(c) and (d) are the optimized hydraulic valve blocks. It can be seen from Fig.11 that the optimized hydraulic valve block removes the excess materials of the traditional valve block, retains the functional characteristics of the valve block, reduces the overall volume of the hydraulic valve block, and is more suitable for AM. It can be seen from Table 2 that, compared with the traditional hydraulic valve block, the optimized hydraulic valve block eliminates all process holes and closed cavities, and its mass is reduced by 33.9%.

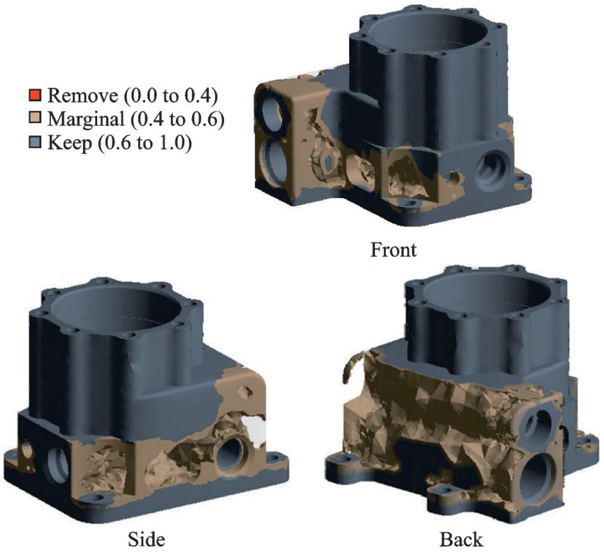
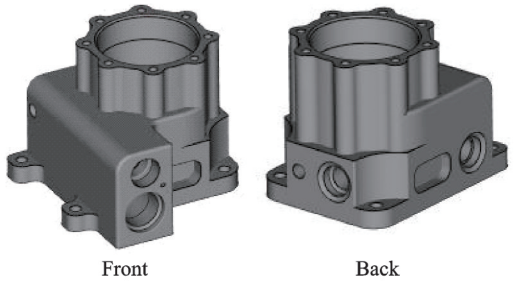
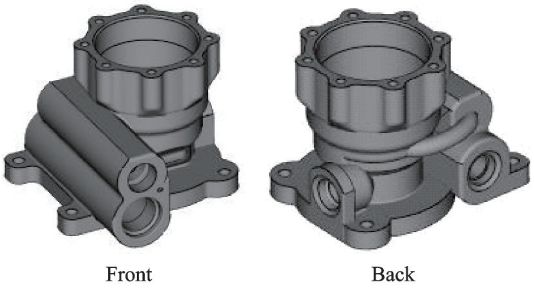


Fig.10 Topology optimization result of hydraulic valve block



(a) Before optimization



(b) After optimization

Fig.11 Hydraulic valve block model before and after optimization

Table 2 Comparison of parameters before and after mass reduction of valve block

Valve block type	Number of craft holes	Number of enclosed cavities	Mass/kg	Percentage of weight loss compared to the traditional valve block/%
Traditional valve block	2	2	0.126 7	
Optimized valve block	0	0	0.083 7	33.9

3.2 Additive manufacturing of valve block

The valve block optimized for weight reduction is manufactured with the aid of AM technology. Before printing the valve block, it is necessary to add support to the valve block and determine the printing direction of the valve block. The printing direction determines the number of supports and the surface smoothness of the parts, and the number of supports directly affects the printing time and printing cost. For this reason, Materialise Magics 22.0 software is used to add printing support to the valve block. Import the valve block into Magics, determine the printing direction of the model, place the model, and then add support to the model. The completed support added model is shown in Fig.12. It can be seen from Fig.12 that the vertical direction of the valve block is the best printing direction of the model, and the vertical printing direction minimizes the number of supports. Because the minimum unsupported 45° angle of AM is considered in the weight reduction optimization design of valve block, the cantilever structure and the number of supports are greatly reduced.

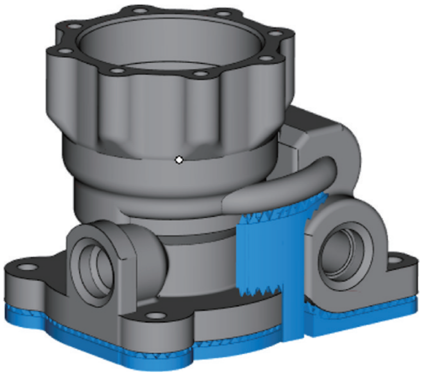


Fig.12 Support addition plan

The valve block is manufactured by adopting the SLM manufacturing method and the German EOS M290 laser selection melting equipment. The maximum forming size of the equipment is 250 mm×250 mm×325 mm, and it is equipped with a 400 W power laser. It is made of titanium alloy powder. The thickness of the powder layer is 30 μm, the scanning speed is 1 200 mm/s, and the powder is spread in one direction. Generally, for holes with a diameter of less than 7 mm, no support is needed during printing. The largest hole diameter of the hydraulic valve block in this article is 7 mm. For the quality of the channel formation, this article adds support inside the holes with a diameter of 7 mm. The completed additive manufacturing valve block is shown in Fig.13.

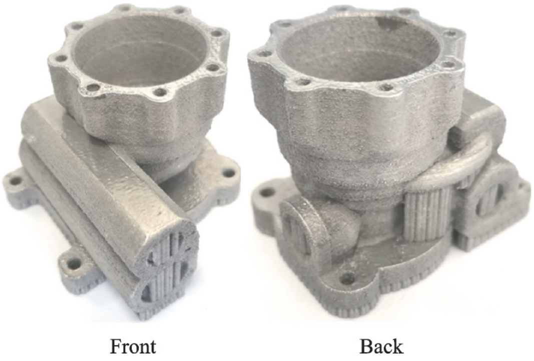


Fig.13 Hydraulic valve block after 3D printing

The surface precision of the valve block through 3D printing has not fully met the assembly and working requirements of the valve block. Therefore, it is necessary to polish the assembly and functional surfaces of the valve block, as well as the surface of the internal flow channel. The outer surface of the valve block and the inner hole surface that the tool can go deep into, are processed by mechanical processing. While the tool cannot go deep into the inner flow channel, the inner surface is polished by abrasive flow. The polishing effect of abrasive flow on the inner surface of the runner is shown in Fig.14. In the figure, the inner surface of the runner polished by abrasive flow is smooth, while the surface of the runner without treatment is rough. Therefore, the abrasive flow polishing method will be adopted in the follow-up research to carry out post-

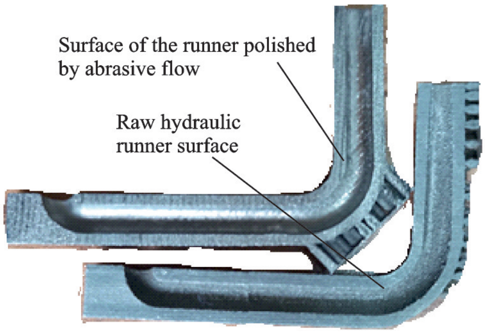


Fig.14 Abrasive flow polishing effect

treatment on the internal flow channel of the hydraulic valve.

4 Conclusions

Based on the AM technology, this paper takes the hydraulic valve block as the research object, optimizes the design of its internal hydraulic flow channel, and validates the optimized design results with CFD analysis. Combining the simulation results of topology optimization, and considering the AM process constraints, the overall weight of the valve block is optimized. Finally, the valve block is manufactured by the SLM method. The relevant research conclusions of this article are as follows.

(1) The hydraulic flow is prone to vortex phenomenon at the right angle turning of the hydraulic flow channel and the closed cavity, and the right angle turning and the closed cavity structure are the main reasons for the pressure drop of the flow channel.

(2) The hydraulic flow channel created by the B-spline curve has a pressure drop of 31.4% lower than that of the flow channel manufactured by traditional mechanical processing methods, and the hydraulic flow channel created by the B-spline curve has a uniform pressure distribution and a stable flow rate. The flow characteristics are better.

(3) The combination of topology optimization and AM technology helps the hydraulic valve block reduce the mass significantly. Compared with the valve block manufactured by traditional machining methods, the mass of the hydraulic valve block made by AM is reduced by 33.9%.

(4) The B-spline technology combined with topology optimization and additive manufacturing technology can better help hydraulic valves improve performance and reduce mass.

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基于增材制造液压阀块及其内部流道优化设计

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摘要：液压阀块是液压系统中重要的组成部分，传统液压阀块采用车铣、钻、镗的方式制造，导致其内部流道有较多直角弯和工艺孔封闭容腔结构，严重影响油液流动性能。基于增材制造技术所提供的新型设计空间，采用B样条曲线对阀块内部液压流道进行优化设计，并对液压流道进行了计算流体动力学分析，以确定压降最小的最优流道结构。通过对液压阀块拓扑优化进行减重，根据拓扑优化结果，采用选区激光熔融的方式，完成了液压阀块的打印。相比原始液压流道，经过优化后的液压流道的压力损失减少31.4%；与原始阀块相比经过拓扑优化并通过SLM制造的液压阀块减重33.9%。因此本文采用的流道优化和阀块轻量化方法为液压阀块内部流道性能提升和阀块整体轻量化设计提供了新的参考。

关键词：流道优化；B样条曲线；压力损失；拓扑优化；增材制造