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Optimal design of metal seated ball valve mechanism

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Abstract A seat is a device mounted in a valve. When a ball valve is in the closed position, the seat seals the ball valve. The seat is usually made from plastic or rubber, so it can be damaged by high pressure or high temperature environments. The objective of this study is to design a new metal seat mechanism for the ball valve. To design a new metal seat, there are four steps to the engineering design process: planning and clarifying the task; conceptual design; embodiment design; detailed design. Some useful tools from the Quality Function Deployment (QFD) technique and the Theory of Inventive Problem Solving (TRIZ) method are used in this design process. The design optimization is completed by the ANSYS package. The novel design of the metal-seated ball valve provides low torque, low wear and long life.

Key words ball valve, metal seat, engineering design, magnetic device

1 Introduction

A valve is a device that controls the flow of fluid, by either preventing (when the valve is in the close position) or allowing (when the valve is in the open position) flow through it. Modern valves can control flow, rate, volume, pressure, and direction of fluid flow for liquids and gases. The valve has a passage, closure member, seat, and steam components, all of which have different functions. When the valve is in the close position, it stops and seals the flow. The valve's sealing function is achieved using a seat component. For secure sealing of the valve in the close position, substances such as plastic, rubber, Teflon, or Nylon may be used as seat materials because of their flexibility. When these materials are under high pressure, at a high temperature, or in a corrosive environment, the seat may be distorted out of shape or destroyed, and therefore will not form an effective seal. A solution to this problem is to replace the plastic seats with metal seats, which can make effective seals, but this is not as easy as it might sound.

The fundamental requirements of a high performance valve are that it works well at high pressure, at high temperature, and in environments with corrosive or hazardous materials. Moreover, the valve should be designed to regulate the flow, to have low torsion, to be cost effective, and to be manufactured, maintained, installed, and removed easily. The use of metal for the seat material is key to achieving high performance. This study describes the design of a new metal seat in a ball valve aimed at achieving these requirements, and which is developed using the mechanical design methodology. The methodology of the mechanical design process, including developing, planning, conceptual design, embodiment design, manufacturing, assembling, and testing were used to obtain a new metal seat in a ball valve.

2 Metal seated ball valve mechanism

A valve is a pressure-containing mechanical device used to stop, allow or modify the flow of a fluid through it. This motion of a valve is achieved by moving the closure element (such as ball, plug, gate and so on). ISA S75.05 offers a formal definition (Borden and Friedmann 1998): "A valve is a device used for the control of fluid flow. It consists of a fluid retaining assembly, one or more ports between end openings and a movable closure member which opens, restricts or closes the port(s)." This is a very broad definition.

There are two major types of valves: linear motion type and rotary motion type(Tullis 1989; Ulanski 1991).

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A linear motion type valve provides shutoff control by raising or lowering the closure member into or out of the flow passage. Gate, globe, diaphragm, and pinch valves are linear type valves used to make a tight seal. The closure member of a linear motion type valve moves with a linear motion to modify the rate of flow through the valve. A rotary motion type valve provides a shutoff control by turning (rotating) the closure member to open and close the flow passage. This type of valve is simple, lightweight, requiring minimum installation space, has a fast response, is easy to operate, automate and maintain, and can be applied to a broad range of services.

The ball valve is one of the rotary motion type valves. It has a ball closure member with a hole through it, as shown in Fig. 1. The ball rotates between seats. The flow is straight through in the open position and blocked when the ball is rotated 90 degrees to its close position. In addition to the advantages of the rotary valve mentioned above, the ball valve has other advantages, such as requiring no lubrication, and giving a tight seal with low torque.

The seat is a part that is assembled in the valve body and may provide part of the flow control orifice. The seat ring may have special material properties and may provide the contact surface for the closure member. The major function of a seat is to make the seal surface with the closure member. Soft materials such as plastics, Teflon, and Nylon are usually used as the seat material because of their flexibility.

An important aspect of the seat is its serviceability. Because the ball is frequently rotated between the open and close position, there may be wear on the seat. When the valve is used under high pressure, high temperature, or in a corrosive environment, the seat may be distorted out of shape or destroyed, and therefore may not be able to seal effectively anymore. A solution to this problem is to replace plastic seats with metal seats, which can make effective seals, but this is not as easy as it might sound.

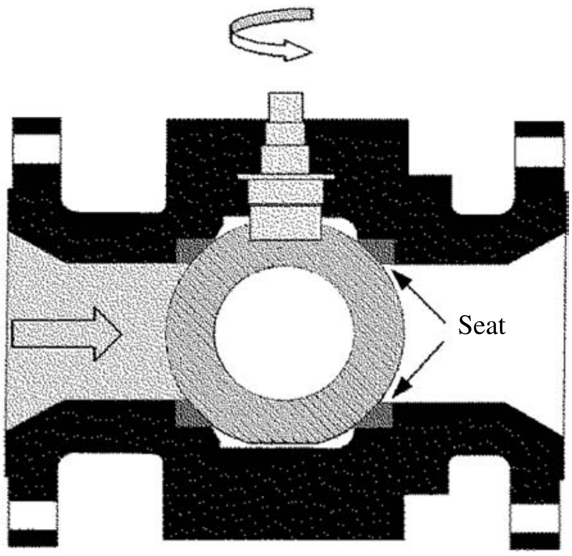


Fig. 1 Ball valve

Manufacture and installation of the metal seat must be done precisely to achieve good reliability, and this increases the cost. When a very tight seal between closure member and metal seat is made, the torque needed to change the position of the closure member is very high. This is the problem that the valve actuator has to overcome in a control valve.

Designing a metal seat to make a tight contact with the closure member is not easy. Therefore, this study is devoted to designing a metal seat that is functional at high pressure, high temperature, and in a corrosive environment, and is easy to manufacture, easy to maintain, and easy to install and remove. Furthermore, the seat should be able to be operated with low torsion, should be low cost, and should regulate the flow evenly.

3 Engineering design process

The systematic engineering design process may help to save design time and ensure successful results. There are several tools widely used in the design process (Pahl and Beitz 1988; Ullman 1992). The Theory of Inventive Problem Solving (TRIZ) is a systematic process that states that contradictions can be methodically resolved through the application of innovative solutions (Altshuller *et al.* 1999; Terninko *et al.* 1998). This theory has three premises: (1) the ideal design is a goal; (2) contradictions help solve problems, and (3) the innovative process can be structured systematically. The process was created by Genrich Altshuller (1926) who analyzed 200 000 patents and found forty problem-solving principles. Many companies and schools use TRIZ for design work.

There are four phases in the engineering design process: planning and clarifying the task; conceptual design; embodiment design;, detail design. Let us take a look at each of these phases in turn.

3.1 Planning and clarifying the task

Several different tools may be applied here, which include (systematically):

The Quality Function Deployment (QFD) method helps to translate fuzzy customer requirements into requirements that are clearly formulated and quantified.

The Theory of Inventive Problem Solving (TRIZ) offers two tools for this phase: the Innovation Situation Questionnaire (ISQ) and Problem Formulation (PF).

The Innovation Situation Questionnaire (ISQ) is the first step of TRIZ. It provides a procedure for gathering the information needed to reformulate a problem and then break it into many smaller problems. This information gathered during ISQ becomes the database for the different TRIZ tools. By answering several specific questions in as much detail as possible, most of the information needed to solve the problem is gathered during ISQ. The answer to these questions forms the basis of the function structure used in Problem Formulation (PF).

PF provides a powerfully systematic process to generate the relationships between primary useful functions (PUFs) and primary harmful functions (PHFs). During the generating process, other relationships between all linked functions (useful and harmful) are built at the same time. The relationships in a PF diagram suggest several types of sub-problems that lead to the problem statements.

3.2 Conceptual design

The role of the conceptual design is to find the main solution after completing the task clarification phase. Abstracting problems, establishing function structures and finding suitable principles can do this.

The Theory of Inventive Problem Solving (TRIZ) offers three tools here. They are Substance-Field Analysis, Contradiction Analysis, and the Ideal Design Process.

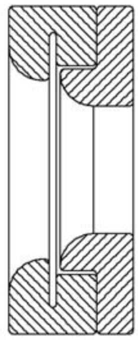
When there are contradiction sub-problems, Contradiction Analysis may help to solve them. The contradictions in TRIZ are separated into technical and physical contradictions. In technical contradictions, the Contradiction Matrix that contains 40 inventive principles provides the solutions. For physical contradictions, they can be solved by the four separation principles. There are three concepts generated from contradiction analysis, as shown in Fig. 2.

Substance-field analysis can suggest ways to beneficially modify the system. There are four steps for structuring the Substance-field model:

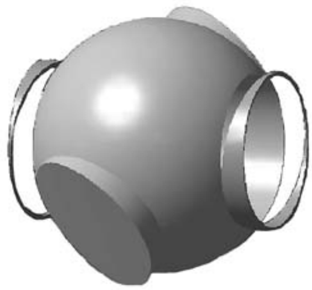
1. Identify the elements
2. Construct the model
3. Consider solutions from the 76 Standard Solutions
4. Develop a concept to support the solution

The ball valve system is described above. Concentrating on the system in a ball valve for the seal, the ball and seat are the interaction substances and the action or interaction (called a field) between the ball and seat is tight contact; this contact is caused by the force. Now there are three elements: ball, seat and mechanical force (two substances and one field). This Substance-Field triangle is shown Fig. 3. The model is complete because the three elements are all identified. The next step is to improve the system for more effective sealing. Therefore, this system can be classified as an ineffective complete system. Using the Substance-Field Analysis suggestion, we apply the standard solutions from classes 2 and 3. After checking all of the related solutions, three possible and realizable directions are chosen. They are magnetic liquids, magnet and electromagnet.

After we complete the concept generation phase, we are left with several concepts. Techniques for choosing



(a) Segmentation concept



(b) Asymmetry concept

(c) Hollow and spiral concept

Fig. 2 Concepts from contradiction analysis

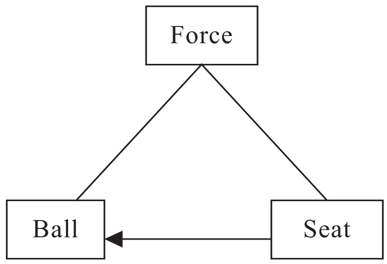


Fig. 3 Substance-Field model

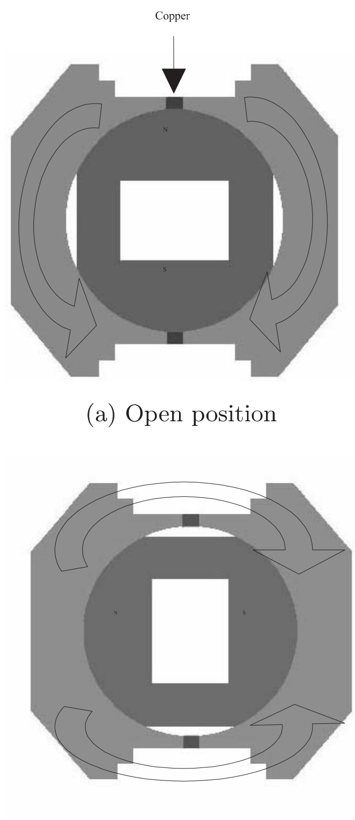
the best of these concepts for development are then explored. The decision-matrix method is fairly simple and effective and can be used to compare concepts that have not been refined enough for direct comparison with the engineering requirements mentioned above. The method provides a means of scoring each concept in its ability to meet the customer's requirements. There are four steps to this method:

1. Choose the criteria for comparison
2. Select the items to be compared
3. Generate scores
4. Compute the total score

For each comparison, the concept is considered to be either better than, about the same as, or worse than the datum. They are denoted as follows:

Better than the datum :	+
About the same as the datum:	S
Worse than the datum:	−

An "S" counts as 0, a "+" as +1, and a "−" as −1. The total is the sum of all numbers, and the weighted total is the sum of each score multiplied by the weighting factors. After calculating the scores, the best concept is the one with the highest score. After calculating the summary scores, the best concept is the magnet. The embodiment design of this concept will be performed in the next design phase.



(a) Open position

(b) Close position

Fig. 4 Magnetic device

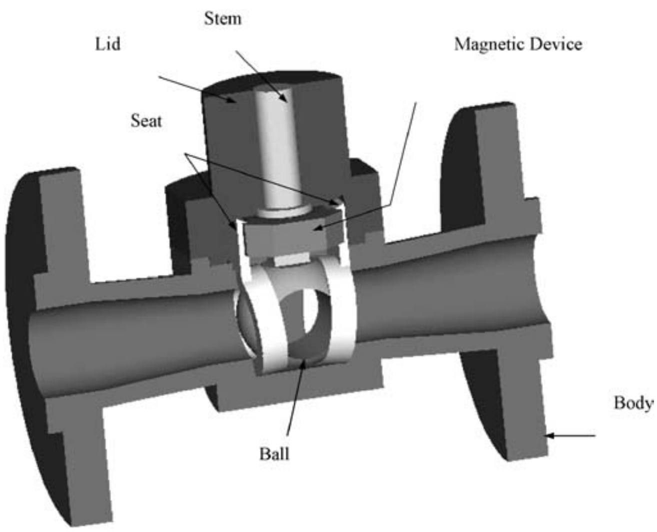


Fig. 5 Final design (R.O.C. Pat. No. 437886, U.S. patent pending)

3.3 Embodiment design and detailed design

When the designers have a concept, the objective of the embodiment design is to construct the structure according to technical and economic criteria. Embodiment design leads to the specification of the layout. The arrangement, types, dimensions and materials of all the individual parts are laid down in the detailed design.

The seat in a ball valve is used to seal in the close position, and usually contacts with the ball. Since the concept uses a magnetic device to help with sealing when in the close position, the magnetic device should apply magnetic force to the seat to aid the seal. When the ball valve is in the open position, the magnetic field will not necessarily be on. If the magnetic circuit produces a magnetic field in close position, but no field in the open position, the friction force in operating ball valve will be less (Parker and Studders 1962).

The shape of the magnetic device is shown in Fig. 4; it is made of three materials. The center cylinder is made of magnetic material, and the outer part of the device is made of iron and copper. Iron is a soft magnetic material, but copper is not. The magnetic lines will flow through iron rather than copper (Chikazumi 1997). When the magnet is in the open position shown in Fig. 4(a), the magnetic lines will pass through the inside part and will not flow outside the device. In the close position shown in Fig. 4(b), if there is a soft magnetic material body near the iron, the magnetic lines will pass through it. Therefore, the body will be attracted by the magnetic force.

After the magnetic device design is complete, the next job is to combine the device with the seat. The seat is a circular ring and this must match up with the ball. In order to receive the magnetic force, a tongue-shaped part

Table 1 Material properties and boundary conditions

Iron relative permeability	100 000
Copper relative permeability	1
Field intensity H	123 000 A/m
Modulus of elasticity E	200 Gpa
Poisson ratio	0.29
Pressure	600 psi
Fixed sides of valve body?	Yes
Symmetric plane	No motion along Z-axis

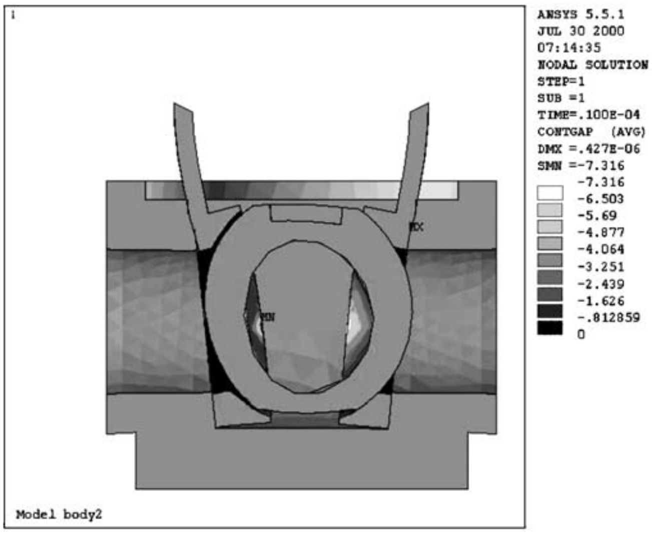


Fig. 6 Contact gap

extending from the rim of the seat is added. The seat now can receive magnetic force in the close position, but not in the open position. To ensure a seal, the seat must be in contact with the ball and the valve body in the close position. For this reason, the hollow space of the valve body that holds the seats and the ball is V-shaped, and the end of the tongue-shaped part of the seat that touches the lid is shaped into an incline (refer to Fig. 5 and Fig. 6). Therefore, the horizontal magnetic force applied by the magnetic device will push the seats downward because of this incline, squeezing the ball and the seats together to ensure the seal. The seat degree of freedom is one, along with the body surface.

The simulation package ANASYS/Multiphysics is the tool used in this study. The meshing element used in the mesh geometry is SOLID98. The material properties and boundary conditions are listed in Table 1.

From Fig. 6, we can see that the contact elements still maintain strong contact with each other, and the gaps between contact elements are zero. This means that the ball valve still seals under pressure.

4 Optimization

Once the magnet is specified, the magnetic force applied to the seats depends on the geometry of the magnetic device. Therefore, the goal of the optimization here is to increase the magnetic force by adjusting the position and dimensions of the magnetic device. Because of the constraint on lid space, and because the the height of the magnetic device can't be changed and the seat orifice part doesn't affect the magnetic lines, the model can be built in two dimensions for the design optimization.

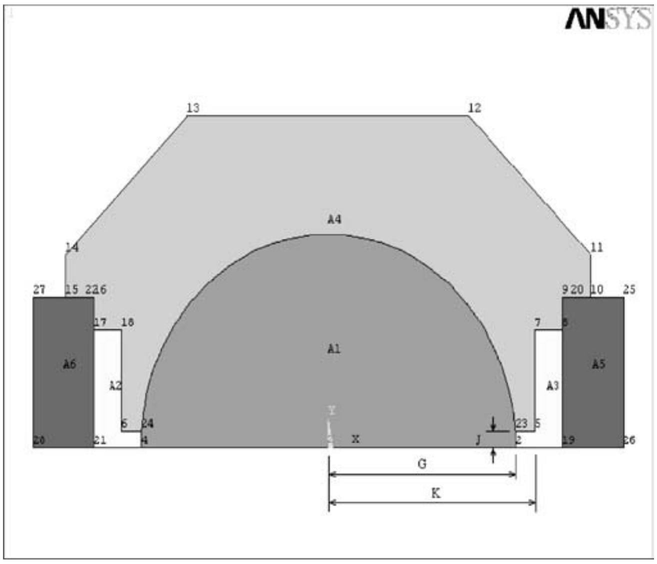


Fig. 7 Optimization model

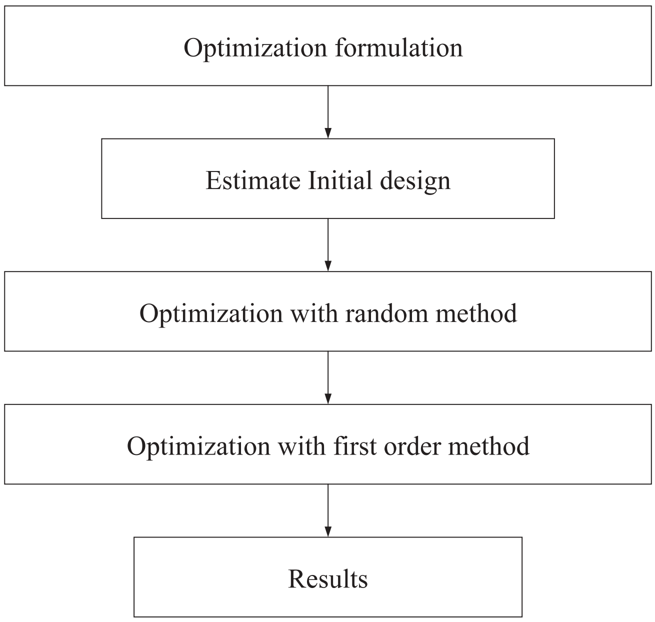
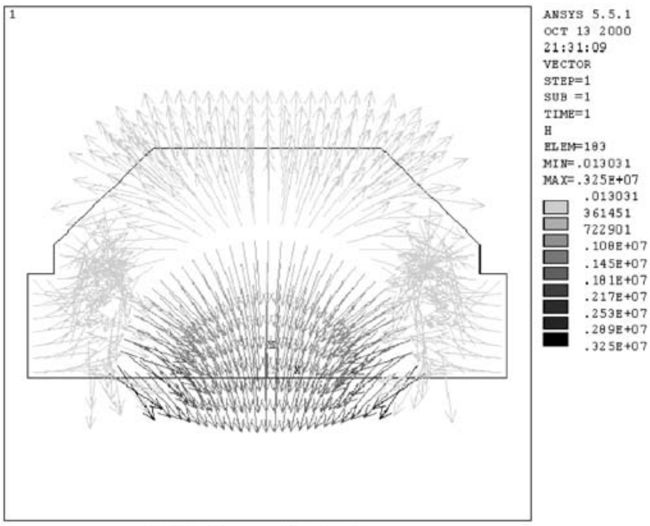


Fig. 8 Optimization process

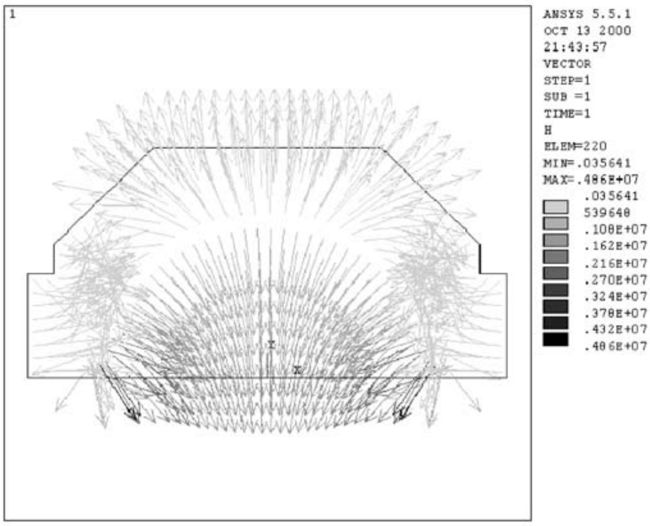
The constraint on the design is the lid space; the magnetic device must be smaller than the lid space. Each parameter has its reasonable constraint determined by the designer. The optimization here is to get the highest magnetic intensity H, because this maximizes the magnetic force. The cost function here is H. The model of the magnetic device is shown in Fig. 7. The lengths J, G and K are design variables. Therefore, the optimization model is outlined as follows:

Table 2 Optimization results

	J	G	K	H
First set	1.5000	20.000	22.000	0.43886×10^7
Best set of random design	3.9883	20.769	21.784	0.58106×10^7
Best set of first-order	2.1020	21.500	22.476	0.62325×10^7



(a) Before optimization



(b) After optimization

Fig. 9 Magnetic intensity vector plot results

Cost function: magnetic intensity H
Constraints: magnetic device is smaller than the lid space
Design variables: lengths J, G, K

The design optimization is completed by the ANSYS package. ANSYS provides Design Optimization tools for solving problems similar to this one. ANSYS provides several different optimization approaches and each has its advantages, such as solution time, accuracy and sensitivity. The ANSYS Parametric Design Language is used to do the iterative process. The ANSYS optimization tool "random tool" is used to better understand the nature and limits of the design space. The random tool generates a wide range of design variable values to make sure that the most feasible design is a global minimum not a local minimum. Then we retain the most feasible solution for further optimization. The first order method of ANSYS is applied to improve the result. The first order method uses gradients of design variables to determine the search direction for subsequent design variable values. This method is more accurate than other ANSYS methods, but takes longer. The optimization process is shown in Fig. 8.

The optimization results are shown in Table 2. The best set for the random design is used as the first set for the first order method for further optimization. After optimization, the magnetic intensity H is higher than for the initial design. This will ensure a greater sealing force. The magnetic intensity vector plot results are shown in Fig. 9.

5 Conclusion

This study used the Quality Function Deployment (QFD) technique and the Theory of Inventive Problem Solving (TRIZ) method to design a new metal seat mechanism in a ball valve. TRIZ offers powerful tools for clarifying a problem and for concept generation. It offers an alternative to traditional thought processes, leading to innovative solutions. After the concepts were generated by the TRIZ process, we used the QFD technique's decision matrix form to evaluate the best one to use for embodiment design. The prototypes can then be designed and manufactured based on the best concept. CAD and CAE software plays an important role in the design phase. The geometry and dimensions of the prototype can be easily defined with the help of CAD software. CAE software simulates and optimizes the prototype condition in a ball valve.

The final prototype is a new concept among metal seat mechanisms. Using a magnet to help seat sealing brings many benefits, including low torque, low wear and long life.

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