Research in the Processes for Manufacturing Matrix-body Curved-profile PDC Bits Using the Method of Fusion and Penetration

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Keywords: Matrix-body; Curved-profile bit; PDC; fusion and penetration (impregnation).

Abstract: As integration of the modern 3D printing technology with the traditional mold manufacturing technology, the method of fusion and penetration is used to produce the matrix-body curved-profile PDC bits. This method includes mainly such processes as the prototype 3D printing, mold copying, mold and material loading, fusion and penetration, and after-treatment. This method is capable of effectively using a variety of materials of special properties at different locations of the bit to ensure it has a reasonable structure and high dimensional accuracy hence ideal application effect, The manufacturing processes are simple with both manufacturing quality and manufacturing efficiency improved.

1 INTRODUCTION

Polycrystalline Diamond Compact ("PDC") bits are a kind of drilling tools commonly applied in the geological industry. Main examples are geological exploration, coalfield drilling (for example, anchor-rod-type PDC bits, and three-wing PDC bits), and oilfield exploration. Among them, the PDC bits used for oilfield exploration are the most expensive and satisfy the most stringent requirements. They can be called "the noble" among PDC bits. A PDC bit consists mainly of the bit body, cutters, nozzles, bit-body outer-wall wear-resistance reinforcement layer, and the joint. Traditional PDC bits have a steel body made of nickel-chromium-molybdenum alloy. Firstly, the alloy stock is machined into the initial bit body. Then the initial bit body is heat treated. After the heat treatment, holes are drilled in the bit body. And man-made PDC cutters are pressed or welded to the crown of the bit body. Finally, the tungsten carbide bars are affixed to the bit-body outer wall for purpose of wear-resistance enhancement. The steel body is notorious for low wear and fracture resistance. Thus the high wear resistance of the PDC cutters is compromised, with the drilling efficiency reduced and the repair or replacement interval shortened. Matrix-body PDC bits as a new type of PDC bits use different materials from those used in traditional PDC bits. They have a matrix body that is made of WC/W2C other than nickel-chromium-molybdenum alloy. Benefits of the matrix-body PDC bits include high wear resistance and drilling efficiency. Using the pressureless impregnation technology, bronze as binder is applied into the structure the skeleton of which is formed by tungsten carbide powder. The matrix body is hence formed. Then, by brazing, PDC cutters are affixed to the crown of the matrix body. Natural diamond bars are attached to the outer wall of the matrix body for purpose of wear-resistance enhancement. The matrix body is shown in Figure 1. Recent years have seen a great change in both quality and variety of matrix-body PDC bits. For example, engineers have optimized the interface between tungsten carbide matrix and PDC cutters. Furthermore, important breakthrough has also been made in the design and arrangement of PDC cutters, with their toughness, abrasion resistance, and thermal stability improved a lot. Nowadays, adoption of new-type smart manufacturing technology makes also a huge contribution to the improvement of the quality of matrix-body PDC bits. These bits possess much greater resistance to erosion and impact. In this paper, the modern 3D printing technology and the traditional mold manufacturing technology are combined to put forth new processes for making matrix-body curved-profile PDC bits. Intention is to overcome the difficulty in machining the crowns that are made of super hard materials and have a quite complex shape. These processes make mass production of the bits possible. These bits hence can be more effectively applied in more industrial fields.

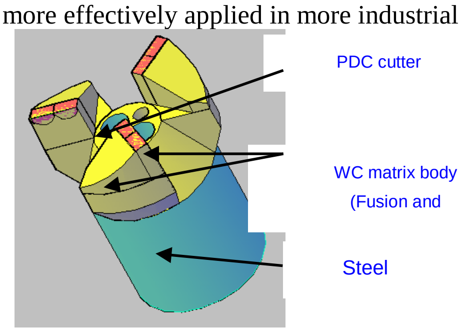

Figure 1 Schematic of matrix-body curved-profile PDC bit.

2 PROCESSES FOR MAKING MATRIX-BODY CURVED-PROFILE PDC BITS

Generally, curved-profile PDC bits have a complex-shaped crown. Two to four cutting wings protrude from the head platform. Three to five PDC cutters are welded to each cutting wing. Gates are prepared in the areas between the cutting wings. Cooling water circulates through these gates while drilling. The entire crown has a curved profile. It is more difficult to manufacture the curved-profile PDC bits. On the one hand, it is more difficult to control the machining accuracy of the curved surfaces; on the other hand, the matrix body is made of the hard materials WC/W2C. Once the curved surfaces are formed, it is difficult to machine them. Furthermore, formation of the cutting wings must ensure the required dimensional and shape accuracy, and the gates and the locations for welding the PDC cutters must be formed during the formation of matrix body. Taking into consideration the structural and material characteristics of the bits, the technology of fusion and penetration (pressureless impregnation) is an effective solution to the mentioned difficulties. Figure 2 shows the flow chart of the technology.

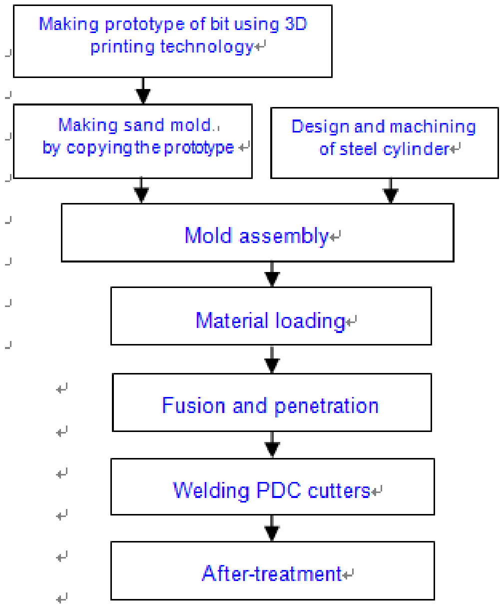

Figure 2 Process flow for making the matrix-body curved-profile PDC bits using the method of fusion and penetration .

2.1 Making Silica Gel Prototype of Bit Using 3D Printing Technology

The primary task for the manufacturing of matrix-body curved-profile PDC bits is to make the silica gel prototype using the modern 3D printing technology. First, the 3D solid model of the bit is built with the design software (for example, PRO/E, UG, CAD, or SolidWorks). With the model modified and analytically optimized, the STL file is directly outputted. Sectioning is then performed. Next, the 3D printing (fused deposition modeling (FDM)) is directly performed to produce the silica gel prototype. The 3D printing technology applies the “dispersion/accumulation” principle for gradual formation. The designers can directly view the model design, and perform the CAE simulation and analysis using the simulation software. This is good for communication, optimization and improvement. The prototype can be made at the specified speed and accuracy. The whole process is both flexible and controllable, removing the need of any tooling. The steps from design to modeling can be completed with a dozen of hours. ABS, wax, and nylon filaments are available for the FDM technique. The modeling temperature is anywhere from 80 to 120ºC, and the modeling accuracy can be 0.1mm. In addition, the after-treatment is simple, the cost is low, and the material utilization rate is as high as 100%. When making the silica gel prototype, Mei

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Xiaoqin[1] adopted a method which additionally incorporated the process for intermediate model conversion. First, she built the 3D model of the bit using the software PRO/E, and converted the 3D model into the model of basic parent mold. Then she got rapidly the basic parent mold using the FDM technique. Finally, she poured silica gel into the basic parent mold to get the prototype of the bit. The process flow of this method is shown in Figure 3. Advantages of this method are effectively implementing the bit structural design, and ensuring the quality of basic parent mold. Disadvantages of this method are adverse influence on manufacturing efficiency and manufacturing cost.

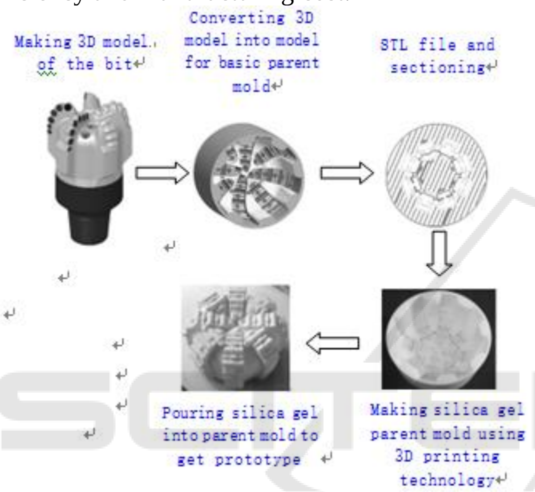

Figure 3 Conversion from model to mold .

2.2 Making Sand Mold By Copying 3D Printed Mold

The silica gel prototype is used for making the clay mold or the sand mold. WC powder is placed in the clay mold or the sand mold, then they undergo the fusion and penetration process in an electric furnace. The matrix body is thereby obtained. Generally, the clay mold is made with the pouring method. Diao Wenqing[2] made the Φ96 matrix body of the PDC bit with the pouring method. First, he performed the design, calculation and machining of the graphite mold casing, and fixed the silica gel prototype. For a sufficiently long time, he mixed steadily a proper amount of clay powder with water according to a certain mixing ratio to get the slurry. Then he poured the slurry into the assembly, thus the cavity between the mold casing and the silica gel prototype was full of slurry. Within half an hour since the completion of the pouring process, the slurry solidified to gain certain strength due to reaction between the clay and the water. He took out the silica gel prototype, to get the clay mold as shown in Figure 4. Finally, the clay mold was dried. This mode was to be used in the fusion and penetration process of matrix body.

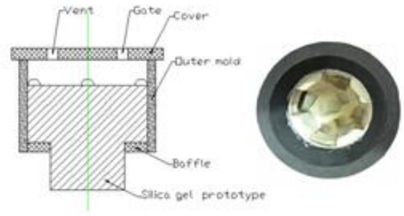

Figure 4 Making the clay mold .

The sand mold may also be used in the process of fusion and penetration of matrix body. Difference in respect of manufacturing process exists between the sand mold and the clay mold. The silica gel prototype is placed in the graphite mold casing. Then the mixture of emery grit, resin adhesive and curing agent is put in the assembly, to fill the cavity. Wait approximately 2 hours for the sand mold solidification. Then directly take the silica gel prototype out of the assembly. The sand is quartz sand with a 200 mesh in grain size, to ensure the matrix body resulting from fusion and penetration has an ideal roughness. The resin adhesive is furan resin or phenolic resin. The mixing ratio of emery grit, resin adhesive and curing agent is 100:1.2:0.6. The sand mold can be made faster and more simply.

2.3 Machining of Steel Cylinder

The steel cylinder is the basic component of the bit. One end of the steel cylinder is tapered, and machined to have shallow rippled grooves, so that the WC matrix body can be consolidated with bronze in the process of fusion and penetration. The consolidation result is acceptable. The other end of the steel cylinder is machined to have female threads, for connection with the drill rod. In case the bit is worn, it can be easily replaced with a new one. The steel cylinder is often made of #45 steel. In addition to machining, it undergoes also the heat treatment process. Both the outer diameter and the inner diameter of the steel cylinder must be in accordance with those of the bit. Inward and outward taped surfaces are arranged where the matrix body is connected to the steel cylinder. To ensure the shape and taper of the outward tapered surfaces, a steel sleeve with a tapered mouth is machined along with the steel cylinder. The steel sleeve will be used in making the clay mold or the sand mold. See Figure 5.

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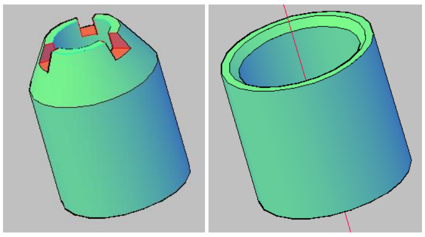

Figure 5 Combination of steel cylinder and steel sleeve.

2.4 Assembly of Mold and Mold Casing

Fix the steel cylinder at the center of the assembly of mold casing and clay mold/sand mold. Gates (i.e. preformed graphite bars) are attached with quick-action adhesive to the locations in the bit for the gates. To the locations for the PDC cutters in the clay mold/sand mold, graphite chips are stuck, which have the same shape and dimensions as the PDC cutters. These graphite chips are prepared in advance, and will be removed with the completion of the matrix body manufacturing, to make room for the PDC cutters to be welded. To the inner wall of the mold casing, polycrystalline diamond bars are stuck. Through the process of fusion and penetration, these bars will be affixed to the surface of the matrix body, serving to enhance wear resistance. See Figure 6.

Figure 6 Assembly of mold and mold casing.

2.5 Material Loading

Materials used for the matrix body are mainly WC or W2C powder, as well as a small amount of metallic materials added for property modification. Referring to table 1, the WC/W2C powder must use a multi-grain-size formula, to ensure the ideal overall compactness and surface quality of matrix body from the process of fusion and penetration. A frequency- adjustable vibrator shall be used for powder loading. The vibrator keeps vibrating the mold casing and the mold, so that the powder flows substantially into the cavity between them. Generally, a small amount of WC/W2C powder is first loaded, to a depth of about 5mm from the end of the steel cylinder. Then more WC/W2C powder is added until the level reaches the bottoms of the cutting wings. Finally, copper-based or ferrous metal-based powder is added to the tapered surfaces at the roots of the cutting wings. The powder serves as connection. The subsequent turning process in a lathe is feasible for these tapered surfaces. See Figure 7. With the powder loading process completed, a certain amount of bronze particles and borax are placed in the clearance between the uppermost mold casing wall and the steel cylinder. Then the assembly can be transferred into the furnace to receive the process of fusion and penetration.

Table 1 Mass ratios of materials used in matrix body.

Powder variety	Grain size (standard mesh)	Mass ratio %
Ni	-100/+325	10
WC/W2C	+70	11
WC/W2C	-70/+100	36~46
WC/W2C	-140/+200	9~15
WC/W2C	-200/+400	18~23
WC/W2C	-400	0~2

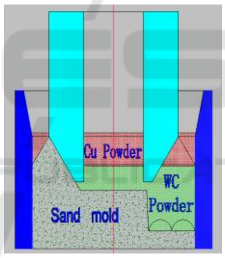

Figure 7 Loading powder in the assembly.

2.6 Fusion and Penetration

The matrix body of the curved-profile PDC bit adopts the technology of fusion and penetration (impregnation). The technology is in the field of powder metallurgy. The whole assembly is heated in the furnace. The heating scheme shall meet the specification. The first stage is heating to somewhere from 1000ºC to 1100ºC; the second stage is temperature holding. All bronze particles melt, penetrating into the voids of the WC/W2C powder skeleton. Result is a compact matrix body. Generally, the heating at the early stage shall be controlled at a slow rate. First, it is good for reliably warming the mold casing and the clay mold or sand mold. Secondly, it is good for slowly volatilizing the resin adhesive and curing agent off the assembly. Be sure to prevent the assembly deformation due to

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rapid heating rate. The entire process of fusion and penetration takes approximately five minutes, with all the bronze particles penetrating the voids of WC/W2C powder skeleton, and the steel cylinder integrated with the matrix body.

2.7 PDC Cutters Brazing

With the matrix body obtained from the process of fusion and penetration, PDC cutters welding is performed to get eventually the PDC bits. First, remove the graphite chips, and clean the locations for welding the PDC bits. These locations shall have no oil stain or oxidation scales. Then, using the copper-based or silver-based welding agent, and the high frequency heating process, weld the PDC cutters to these locations. Equipment used for making PDC cutters is a six-acting-face high-temperature, high-pressure press. Usually, the PDC cutters have a regular shape, cube, prism, or cylinder. The welding agent is of copper-based, silver-based, aluminum-based, or nickel-based alloy, with a melting point above 450ºC. With the welding in progress, the fluxing agent is added, such as borax, boric acid, chloride, or fluoride. The high-frequency electric induction heating/welding yields a good many benefits, such as simple operation, being free of local deformation, high welding strength, considerable material saving, and excellent mechanical behaviors.

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2.8 After-treatment

The after-treatment processes mainly refer to the machining of the tapered surfaces of ferrous metal-based powder from fusion and penetration, and the finishing of the edges, corners, and surfaces. In addition, the parts temporarily used for the formation of the gates must be removed. Machining methods include turning, drilling, milling, and sand blasting.

3 CONCLUSIONS

The technology of fusion and penetration used for making the matrix-body PDC bits consists mainly of such processes as making the prototype using the 3D printing technology, making the clay mold or sand mold by copying the 3D printed mold, material loading, fusion and penetration, and after-treatment. As integration of the modern 3D printing technology and the conventional mold manufacturing technology, the method of fusion and penetration is capable of effectively applying a variety of materials of special properties at different locations on the bit, to form a gradient mechanical properties system. Moreover, this method is capable of ensuring the required structural and dimensional accuracy of PDC bits. The products are notable for fairly good application results. Their manufacturing processes are simple, with the manufacturing quality and manufacturing efficiency enhanced.

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