Research and application of efficient milling process for surface casing

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Abstract. In order to solve the problems in the surface casing removal, the casing milling process is proposed to be used. Through the size and material selection of casing milling pipe, mechanical analysis of connection thread and the innovative design of casing milling shoes, a series of casing milling tools and the efficient casing milling process are formed. The field application results show that the milling process can smoothly mill to the predetermined position. After the milling process, the surface casings can be successfully removed by cutting and fishing. The efficient milling process studied in this paper can make the removal of the surface casing with low cost and high efficiency. Both social and economic benefits are remarkable and it has a broad application prospect.

1. Introduction
With the continuous expansion of urban scale in North China especially the vigorously growing of Xiong'an New Area, more oil, gas and water wells are increasingly included in the scope of urban reconstruction. The well pattern distribution in oilfield development blocks is complex. Therefore, it is difficult to test the construction of urban underground pipe network and rail transit in the future. It is necessary to seal the oil, gas and water wells in the scope involved and take out the surface casing at a distance to restore the natural landscape. How to remove the surface casing with low cost and high efficiency has become a key problem to be solved.

The wellbore structure of oil, gas and water well can be divided into tubing, reservoir casing and surface casing. The surface casing and the formation are cemented by cement. As is shown in Figure 1, the cementing surface area between cement and formation is huge. So the axial pile pulling force far exceeds the tensile strength of the casing. And outside the cement are loose stratum, in case of sticking and other accidents, the annular space is small and it is difficult to deal with [1]. And now, for surface casing removal, there is no supporting technology. In view of the above, it is necessary to study the casing milling technology of surface casing. It has a broad application prospect.
2. Design and optimization of casing milling tools

Casing milling is a process which is used to remove various objects between the downhole string and the wellbore to release the string [2]. Figure 2 is the schematic of casing milling. The casing milling tools include casing milling pipe and casing milling shoes. The casing milling tool rotates by applying torque to mill. So the design and optimization of casing milling tools count for much.

2.1. Optimization of casing milling pipe

The outer diameter of casing milling pipe should be smaller than the outer diameter of cement ring, and the inner diameter of casing milling pipe should be larger than the outer diameter of surface casing. The larger the diameter of the casing milling pipe, the greater the axial pressure and the torque that are required [3]. Therefore, in the case that enough space is left for milling fluid circulation, the diameter of casing milling pipe should be as small as possible.

At present, the common outer diameter of the surface casing in Huabei Oilfield are 339.7mm and 273mm. According to the SY5487-92 casing milling pipe standard and API Sepc5CT standard, the type TXG406.40-16.66 and TXG339.72-13.06 of the casing milling pipe can be selected. Table 1 shows the specific parameters of the casing milling pipe.

The casing milling pipe must bear great tensile stress, torque and bending stress in use. Therefore, it is necessary to have good tensile and bending strength as well as good toughness. At present, the commonly used materials for casing milling pipe are N80, X95 and P110.
Table 1. Specific parameters of the casing milling pipe.

| Type            | Outer Diameter(mm) | Inner Diameter(mm) | Wall Thickness(mm) |
|-----------------|--------------------|--------------------|--------------------|
| TXG339.72-13.06 | 339.72             | 313.60             | 13.06              |
| TXG406.40-16.66 | 406.40             | 373.08             | 16.66              |

The minimum tensile strength ($\sigma_b$) of N80 material is 679MPa, the yield strength ($\sigma_{0.5}$) is 537~788MPa. The minimum tensile strength ($\sigma_b$) of X95 material is 724MPa, the yield strength ($\sigma_{0.5}$) is 655~862MPa. And the minimum tensile strength ($\sigma_b$) of P110 material is 862MPa, the yield strength ($\sigma_{0.5}$) is 758~965MPa.

The relationship between the allowable tensile stress and yield strength of the casing milling pipe is:

$$[\sigma] = \frac{\sigma_{0.5}}{n}$$

(1)

The relationship between axial force and allowable tensile stress is:

$$[\sigma] = \frac{F_{\text{max}}}{A}$$

(2)

$$A = \frac{\pi (D^2 - d^2)}{4}$$

(3)

Among them, $[\sigma]$ is allowable tensile stress, $n$ is safety factor and is generally 1.6-2.5, $F_{\text{max}}$ is axial force, $A$ is sectional area, $D$ is the outer diameter of casing milling pipe and $d$ is the inner diameter of casing milling pipe.

The maximum torque $T_n$ that the casing milling pipe can bear satisfies the following relationship:

$$T_n = W_p \cdot [\tau]$$

(4)

$$W_p = \frac{\pi D^3}{16} \left[1 - \left(\frac{d}{D}\right)^4\right]$$

(5)

$$[\tau] = 0.6 \sim 0.8[\sigma]$$

(6)

Among them, $W_p$ is torsional modulus and $[\tau]$ is allowable shear stress.

Substitute the internal and external diameter dimensions of the TXG406.40-16.66 and TXG339.72-13.06 casing milling pipe into the above formula respectively. It can calculate the allowable axial force and allowable torque of the casing milling pipe with different materials and different specifications. Table 2 and Table 3 show the calculation results.

Table 2. Allowable axial force of the casing milling pipe.

| Type            | N80(KN) | X95(KN) | P110(KN) |
|-----------------|---------|---------|----------|
| TXG339.72-13.06 | 1439.44 | 1755.74 | 2031.83  |
| TXG406.40-16.66 | 2190.80 | 2672.21 | 3092.34  |

Table 3. Allowable torque of the casing milling pipe.

| Type            | N80(KN) | X95(KN) | P110(KN) |
|-----------------|---------|---------|----------|
| TXG339.72-13.06 | 52843   | 67484   | 82637    |
| TXG406.40-16.66 | 81921   | 99922   | 11567    |

From the results, we can see the N80 casing milling pipe can meet the requirements of surface casing milling and it has the lowest cost.
2.2. Mechanical analysis of connection thread of casing milling pipe

The thread connection of casing milling pipe is used for the connection between every casing milling pipe and also between the casing milling pipe and the rotary top drive [4]. The rotary top drives transmits torque to casing milling pipe, so that the casing milling pipe can rotate under a certain pressure and torque. So during the casing milling, the threads withstand rotating torque and axial pressure. After the casing milling, in the process of raising the casing milling pipes, the threads withstand axial tension. Therefore as the weakest link, the thread needs to meet a certain intensity.

According to the SY5487-92 casing milling pipe standard, the type of threads are double stage partial trapezoid short tooth synchronous thread or double stage square short tooth synchronous thread. Compared with the conventional single-stage thread, the double-stage thread has the advantages of easy coupling, fast bucking speed, strong resistance to longitudinal impact and vibration etc. Meanwhile, the double stage partial trapezoid short tooth synchronous thread is non-isosceles trapezoid thread, it is better for neutral and stronger for connection. So we choose this type of threads. The tooth profile is shown in Figure 3.

![Figure 3. The tooth profile of double stage partial trapezoid short tooth synchronous thread.](image)

In order to check the strength of the thread, we use the finite element software ANSYS to analyze the stress and strain of the screw thread. The type TXG339.72-13.06 casing milling pipe is selected as the research object. Ignore the asymmetric factor of screw structure and the influence of helix angle to simplify the model. The load on the casing joint is mainly the axial tension with symmetrical distribution. Therefore, the casing thread joint can be treated as a two-dimensional axisymmetric problem. Using the parameterized modeling method is convenient and efficient, which is beneficial to the improvement and perfection of casing thread [5]. The model diagram of the double stage partial trapezoid short tooth synchronous thread is shown in Figure 4.

![Figure 4. The model diagram of double stage partial trapezoid short tooth synchronous thread.](image)

According to test data and load conditions, we choose the isotropic elastic-plastic material as the material of the casing thread joint model. The elastic modulus is 210GPA and the Poisson ratio is 0.3. Considering the low strain rate and non-cyclic loading, it is assumed that the material obeys the isotropic hardening law. The plastic strain is 0.139 when the material fails, which is regarded as the failure condition of the material [6].The friction coefficient between the contact surfaces is 0.08. And at the construction site, the maximum allowable WOB is 60KN. Apply 100kN axial pressure to the model to analyze the stress situation. The stress nephogram of the male and female buckles are shown in Figure 5(a) and Figure 5(b).
As can be seen from Figure 5 above, there is no obvious stress concentration and the maximum stresses of the male and female buckles are 14.181Mpa and 14.87Mpa respectively. It is far less than the yield limit of the material, so this connection thread of the casing milling pipe can meet the requirements of mechanical properties.

2.3. Structure design of casing milling shoe

The structure of common casing milling shoe is very simple. It just weld the cemented carbide to the casing milling pipe. This kind of casing milling shoe has low strength, easy to tear and can’t meet the requirement of long-term continuous operation. Secondly, in the process of casing milling, there is not enough annulus clearance, so that the circulation of casing milling fluid is not smooth and the cement debris cannot be discharged. The risk of sticking is relatively high. Therefore the casing milling shoe must be designed with water holes and appropriate inner and outer diameter size to make the casing milling fluid circulate fully and the milling part should have high hardness and toughness to bear great impact load.

For the structure of the casing milling shoe, three kinds of gear structure are selected for comparative test and analysis. They are the great wall gear milling shoes, PDC gear milling shoes and the wave gear milling shoes. The 3D model diagrams of the three kinds of milling shoes are shown in Figure 6(a), Figure 6(b) and Figure 6(c).
In the comparative test, the three kinds of milling shoes are used for casing milling in three wells with similar well conditions. The results are as follows:

1. The great wall gear milling shoe mills 21.66m in total. In the early stage, the milling speed is relatively fast, but with increasing depth, the speed becomes unusually slow. And it is too hard to mill at the depth of 21.66m. The comprehensive milling speed is 0.39m/h. So it can be concluded that the great wall gear milling shoe is mainly depends on the grinding effect of the great wall gear after adding WOB, the speed is slow and it is not suitable for milling cement.

2. The PDC gear milling shoe mills 53.14m in total. The PDC gear cutting speed is fast, and the instantaneous speed can reach 2-3m/h. The comprehensive milling speed is 0.95m/h. Although the effect of cutting and destroying cement is good, but the PDC gears have high cost and are easy to collapse.

3. The wave gear milling shoe mills 40.31m in total. The whole milling process is relatively stable. And the comprehensive milling speed is 0.67m/h. Compared with the great wall gear milling shoe, the wave gear milling shoe has obvious improvement of cutting and destroying cement. However for the PDC gear milling shoe, the milling speed of wave gear milling shoe is relatively slow.

From the results above, it can be seen that the wave gear milling shoe has overall performance. Therefore, an efficient casing milling shoe with improved wave gears is designed. The 3D model diagram and the profile are shown in Figure 7(a) and Figure 7(b). And the picture of the real product is shown in Figure 8.

Figure 7. The 3D model diagrams of the new wave gear milling shoe.

Figure 8. The picture of the real product.
The design of inner and outer gears are added to the new wave gear milling shoe, and there are a certain number of water holes in the milling shoe. So, it has better effect on cement cutting and has enough annulus clearance for the circulation of casing milling fluid so that the cement debris can be discharged smoothly. The cemented carbide particles are evenly inlaid on the surface of the wave gears, the rockwell hardness can reach 93HRA and the compressive strength can reach 6000MPa. The new wave gear milling shoe is also used for casing milling test. It mills 83.67m in total. The comprehensive milling speed can reach 1.36m/h and the whole milling process is very stable. To sum up, the new wave gear milling shoe has excellent performance.

3. Field application

3.1. The overall application situation

Xiong'an New Area was established in 2017. According to the Hebei Xiong'an New Area planning outline, all oil, gas and water wells involved in the new area shall be withdrawn before 2025. Huabei Oilfield Company attaches great importance to this situation and has carried out a lot of preliminary work. Up to now, the efficient milling process for surface casing has been applied in 3 wells. The Table 4 shows the overall application situation.

| Well number | Surface casing(mm) | Casing milling pipe(mm) | Casing milling shoe(mm) | Penetration rate (m/h) | Torque (KN•m) | Milling time (hour) |
|-------------|--------------------|-------------------------|-------------------------|-----------------------|---------------|-------------------|
| B116X       | 273                | 339.7*13.06             | 350                     | 1.34                  | 5-14          | 77                |
| B107X       | 339.7              | 406.4*16.66             | 445                     | 1.17                  | 5-15          | 85                |
| Y9-30       | 273                | 339.7*13.06             | 350                     | 1.25                  | 5-13          | 80                |

The well B116X and well B107X occupy the construction line of Jing-xiong high speed railway, and the Y9-30 well locates in Baiyang Lake buffer zone. All three wells are smoothly milled to the predetermined position by using the efficient milling process for surface casing, after that, the surface casings are successfully removed by cutting and fishing.

3.2. Application example

Take well B116X as an example. The outer diameter of surface casing is 273mm, the type of the casing milling pipe is TXG339.72-13.06 and the outer diameter of casing milling shoe is 350mm. The BHA is: D350mm casing milling shoe+D339.7 casing milling pipe+D339.7 to D127mm adapter+Kelly bar.

The surface casing milling construction started on March 13, 2019 and ended on March 23, 2019. During the whole process, the drilling pressure is 5-50KN, the rotation rate is 30r/min and the displacement of milling fluid is 32L/s. Table 5 is the engineering parameter table.

As seen from the table, with the increase of well depth, the drilling pressure increases gradually, the rotation rate is kept at 30r/min and the displacement is kept at 32L/s all the time. The whole process is stable. There is no debris accumulated in the well. The Figure 9 shows the photos of the spilths from the well. The maximum diameter of them is 21mm, this has no effect on the surface casing milling.
Table 5. Engineering parameter of the surface casing milling construction.

| Well depth(m) | Drilling pressure(KN) | Rotation rate (r/min) | Displacement (L/s) | Pump pressure(Mpa) | Density (g/cm³) | Viscosity (mPa•s) |
|---------------|-----------------------|-----------------------|--------------------|--------------------|----------------|------------------|
| 0-10.5        | 5-20                  | 30                    | 32                 | 0                  | 1.15           | 45               |
| 10.5-21.6     | 20                    | 30                    | 32                 | 0                  | 1.06           | 43               |
| 21.6-98.4     | 30                    | 30                    | 32                 | 0                  | 1.07           | 44               |
| 98.4-101      | 35-40                 | 30                    | 32                 | 0                  | 1.07           | 43               |
| 101-109.9     | 40-50-20              | 30                    | 32                 | 0                  | 1.06           | 44               |

Figure 9. The photos of the spilths.

One casing milling shoe is used in the milling process of this well. Figure 10 shows the photo of the casing milling shoe. The size and specification of the casing milling shoe has not changed after lifting out. The cemented carbide particles on the top of the casing milling shoe are rounded by milling and there is a small absence of cemented carbide particles on the side of the casing milling shoe body. There are some scratches on the inside side of the casing milling shoe, which are determined to be caused by the cement block falling between the casing milling pipe and the surface casing. Overall, after the milling the casing milling shoe is also in good condition. So, the designed new wave gear casing milling shoe is fully competent for the milling operation of the surface casing.

Figure 10. The photo of the casing milling shoe which is removed from the well.
4. Conclusions

(1) With regard to the casing milling process, casing milling tools are designed and optimized. Through the selection of casing milling pipe, mechanical analysis of connection thread and innovative design of casing milling shoes, a series of casing milling tools and the efficient casing milling process are formed.

(2) The efficient milling process for surface casing is applied in 3 wells. All three wells are smoothly milled to the predetermined position and the surface casings are successfully removed by cutting and fishing.

(3) The efficient milling process which is studied in this paper can be applied to the surface casing removal. The process is mature and reliable. It has a broad application prospect.

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