Pressure Bearing Capacity Investigation into A Downhole PGA Frac Ball

Jun Liu, Zhenjia Liu*

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, 610500, China.

*Corresponding author: 214865612@qq.com. photo:18160098455.

Abstract

Polyglycolic acido (PGA) material has good application prospects in oil&gas well frac operation because of its excellent compressive strength, degradation and no damage to wellbore environment. Pressure bearing capacity is an important index for the performance of downhole PGA frac ball. However, the research on the bearing capacity of fractured ball is still very limited. Four sets of material compression tests were carried out, and the true stress-strain constitutive relationship of PGA materials was obtained. The finite element model (FEM) of PGA frac ball was established and is verified by comparing the numerical simulation results with that of PGA frac test. Further, considering the interaction between the frac ball and the ball seat, the numerical simulation model of downhole PGA frac ball is established is verified by the test results of downhole frac PGA ball. Using the numerical model, the influence of the ball seat supporting angle, the radius of the end corner, the difference between the ball seat inner diameter and the frac ball (DBF) on the bearing capacity of the PGA frac ball is investigated. The angle of supporting surface can not be too big or too small, the most suitable angle is between 24°-27°. The roundabout angle can improve the bearing capacity of the frac ball, and the suitable radius of the circle is 5-15mm. The DBF has great influence on the bearing capacity of the frac ball. The greater the DBF, the better the bearing capacity of the frac ball. However, after a certain value, the DBF has little effect on the increase of the bearing capacity, and the displacement of the oil and gas wells will be reduced, moreover, the small ball diameter will affect the oil and gas displacement.

Keywords

Downhole tools; PGA frac ball; Pressure bearing capacity; Experimental analysis; Finite element simulation.

1. Introduction

For the purpose of low cost and high efficiency in unconventional oil&gas development, more and more attentions (Chen et al, 2007) have been paid on the packer-sleeve multi-interval fracture technology (Fig. 1) which can realize the purpose of the multi-layer fracturing with pipe string in one trip, and has the advantages of simple operation, good sealing effect and low operating cost. The ball used to open the slip sleeve in fracturing is one of the key factors to determine the success of fracturing.

There are two kinds of fracturing balls commonly used at present, steel balls and resin ball (Wang et al, 2007) such as caseing resin ball and its composite ball, epoxy resin ball and its composite ball, nylon ball, polyionic ball, glass fiber or carbon fiber reinforced polyionic ball. These conventional fracturing balls have the following problems (Stivers et al, 2013 and J. Griffin et al, 2013): (1) in multi-stage hydraulic fracturing, when the throwing velocity changes abruptly, the fracturing balls made of nylon and other materials will deform and become stuck in the slip sleeve to block the production channel after fracturing, resulting in a decline in production; (2) when the horizontal section length is long or the number of fracturing stages is large, the recovery or removal of fracturing balls will become difficult, reducing the production efficiency of oil&gas well.

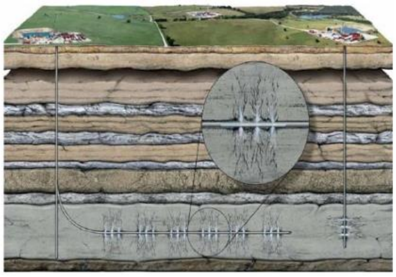


Fig. 1 Multi-section frac in horizontal well

Fig. 2 PGA frac ball

In order to solve these problems, the existing research focus is gradually put on degradable fracturing balls such as water-soluble perforated seal ball (Bilden et al, 1998), nano metal frac ball (Agrawal et al, 2011), metal based frac ball(Liu et al, 2016) aluminum frac ball (Teng et al, 2016), magnesium alloy decomposition frac ball (Pei et al, 2014) , disintegrable nano-engineered composite (Salinas et al, 2014), etc. which do not need to be recycled, degrade completely on the ball seat, have no residue, and do not affect the production capacity of oil&gas wells.

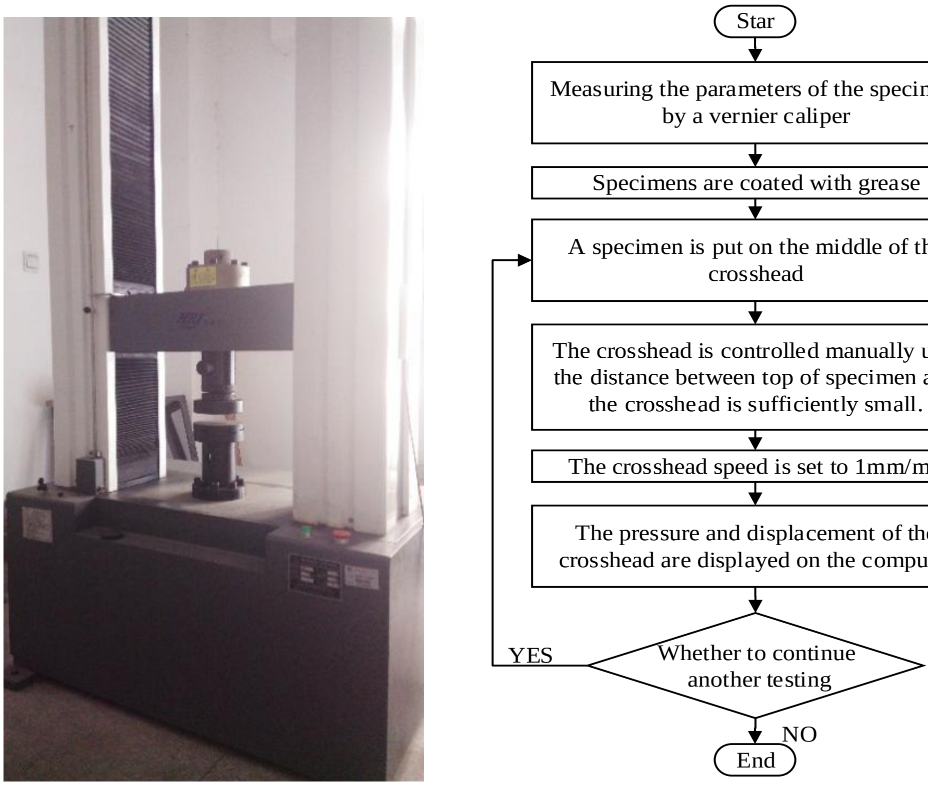
Compared with other similar degradable polymers, polyglycolic acido (PGA) material has significant advantages: complete biodegradability, fast degradation rate, good heat resistance, excellent gas barrier performance and high mechanical strength. Therefore, PGA material has shown a very high application prospect in the field of oil&gas exploitation, especially for fracturing ball (Okura et al, 2015; Zou et al, 2016; Yamane et al, 2014;) (Fig. 2).

Aviles et al (2013) pointed out that an excellent decompressed frac ball needs to meet two basic conditions: good self-degradation in aqueous solution and high pressure bearing capacity. Some researchers have studied PGA fracturing balls in these two aspects. Takahashi et al (2016) presented a method to improve pressure bearing capacity of PGA materials by adding glass fiber(G-P). A simplified mechanical model of slip sleeve and fracturing ball and its experiment verification was presented by Feng et al (2013). They pointed out that the deformation of fracturing ball is the fundamental reason for the jamming of fracturing ball. The strength of fractured ball and the improvement of sphere seat have been studied by Shang et al (2015). It is pointed out that the arc socket has more advantages than the traditional socket in improving the bearing capacity of the fractured ball. A FEM model of the aluminum alloy frac ball and ball seat was carried out by Zheng et al (2016) to investigate the stress, strain and deformation distribution of frac ball under different pressure. Garza (2017) presented a new polymer frac ball, and conducted differential pressure tests on two types of ball seats at different temperatures. Zhou et al(2018) found in their field test that the bearing capacity of frac ball is the best when the cone angle of ball seat is 25°.

At present, the study focus of the frac ball mainly is put on how to improve material strength. Few works about the bearing capacity of a downhole frac ball have been reported. In this paper, firstly, the stress-strain relationship curve of the PGA material was determined by a compression experiment. Secondly, using the relationship curve and ABAQUS software, the finite element model of a downhole PGA frac ball taking into account the interaction between ball and ball seat is established, and the influence mechanism of key structural parameters on the bearing capacity of PGA fracturing balls is investigated.

2. Mechanical properties of PGA frac ball under compression condition

In this section, using the microcomputer controlled electrohydraulic servo universal testing machine (model WDW-200, Fig. 3(a)), a material compression test is performed to determine the material property parameters of PGA frac ball and the true stress-strain relationship used in finite element software (FEM) ABAQUS. The detailed flow chart of the experiment is shown in Fig. 3(b).



(a) (b)

Fig. 3. (a)Microcomputer controlled electrohydraulic servo universal testing machine (b)Flow chart of compression test

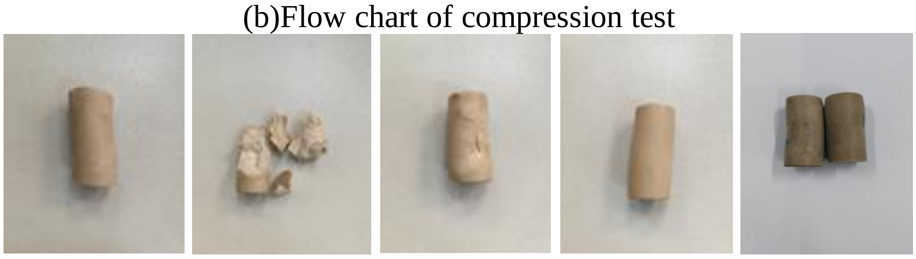


Fig. 4 Specimens after frac test

Four groups of cylinder specimens were used in the test, with the sizes (Length*Diameter (mm): 30.05*11.9, 29.90*11.90, 29.94*11.91, 29.97*11.91). In the test, the top and bottom of specimens were coated with grease to reduce the effects of the large friction force between the specimens and the crosshead. Moreover, the specimens were requested to installed in the center of the crosshead to reduce the influence of shear stress. In order to obtain more accurate results, the loading speed which was determined by the moving speed of the crosshead was limited to less 1mm/min. The pressure and displacement of the crosshead were transmitted to the computer in real time until the specimens were crushed. The specimens after test are shown in Fig.4 and the compressive force-displacement curve is shown in Fig. 5. It can be seen from the Fig. 5 that PGA material has no obvious yield platform, and its yield limit and strength limit are very close. Therefore, to be used in ABAQUS software, the force-displacement curve is converted to real stress-strain data (Fig. 6), using the following derivation.

The definition of real stress and strain:

$$\sigma = \frac{F}{A}, \varepsilon = \frac{\Delta l}{l} \tag{1}$$

where F is de axial pressure load on the two ends of the specimen, l is the length, A is the cross-sectional area.

The definition of engineering stress and strain:

$$\sigma_n = \frac{F}{A_0}, \varepsilon_n = \frac{\Delta l}{l_0} = \frac{\int_{l_0}^{l} \mathrm{d}l}{l_0}, d\varepsilon_n = \frac{\mathrm{d}l}{l_0} \tag{2}$$

According to Eqs (1) and (2), the strain and stress of the specimen are obtained

$$\varepsilon = \int_{l_0}^{l} \frac{\mathrm{d}l}{l} = \ln\frac{l}{l_0} = \ln(1+\varepsilon_n) \tag{3}$$

$$\sigma = \frac{F}{A} = \frac{F}{A_0}\frac{l}{l_0} = \sigma_n(\frac{l}{l_0}) = \sigma_n(1+\varepsilon_n) \tag{4}$$

Elastic strain is also subtracted from plastic strain:

$$\varepsilon^{pl} = \varepsilon^{t} - \varepsilon^{el} = \varepsilon^{t} - \frac{\sigma}{E} \tag{5}$$

Three displacement-compressvie force curves (Fig.5) obtained in the test are converted to a stress-strain curve (Fig.6) to describe the elastoplastic properties of PGA material. According to the stress-strain curves, the Yong’s modulus and Poisson's ratio are respectively determined as 7.2GPa and 0.33.

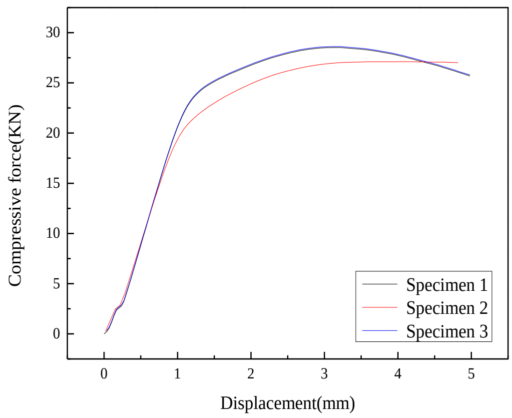


Fig. 5 Compressive force-displacement curve

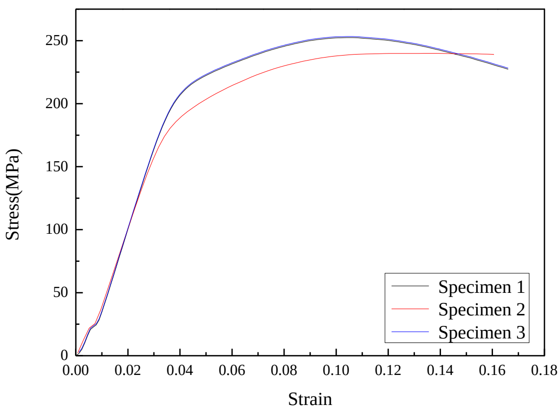


Fig.6 Compressive stress-strain curve

3. Establishment of PGA numerical simulation model

In this section, a finite element model of PGA fracturing ball-ball seat is established in which the material constitutive of the fracturing ball is described by the compressive stress-strain curves shown in Fig. 6. Density and 1.27g/cm^3. The ball seat is made of Q235 steel and is completely fixed. The diameter of ball is 0.034m, and the inner diameter of seat is 0.031m. Inner surface of the seat and external surface of the frac ball are respectively defined as main surface (red) and subordinate surface (magenta). Load and boundary conditions were applied to the model. The loading of the top half part of the ball was applied, the boundary condition, the bottom of the seat, was fixed. The rotation direction of the frac ball was restricted in X Y Z directions, so that it did not shake (Fig. 7). The SOLID187 unit used in the sphere seat and fracturing sphere is 118137 units in total. Linear reduction integral is adopted. In order to make the results more accurate and high computational efficiency, the number of cells can be increased at the contact position. The maximum MISES stress of the contact surface is analyzed emphatically, so the number of cells increased two times at the roundabout of seat.

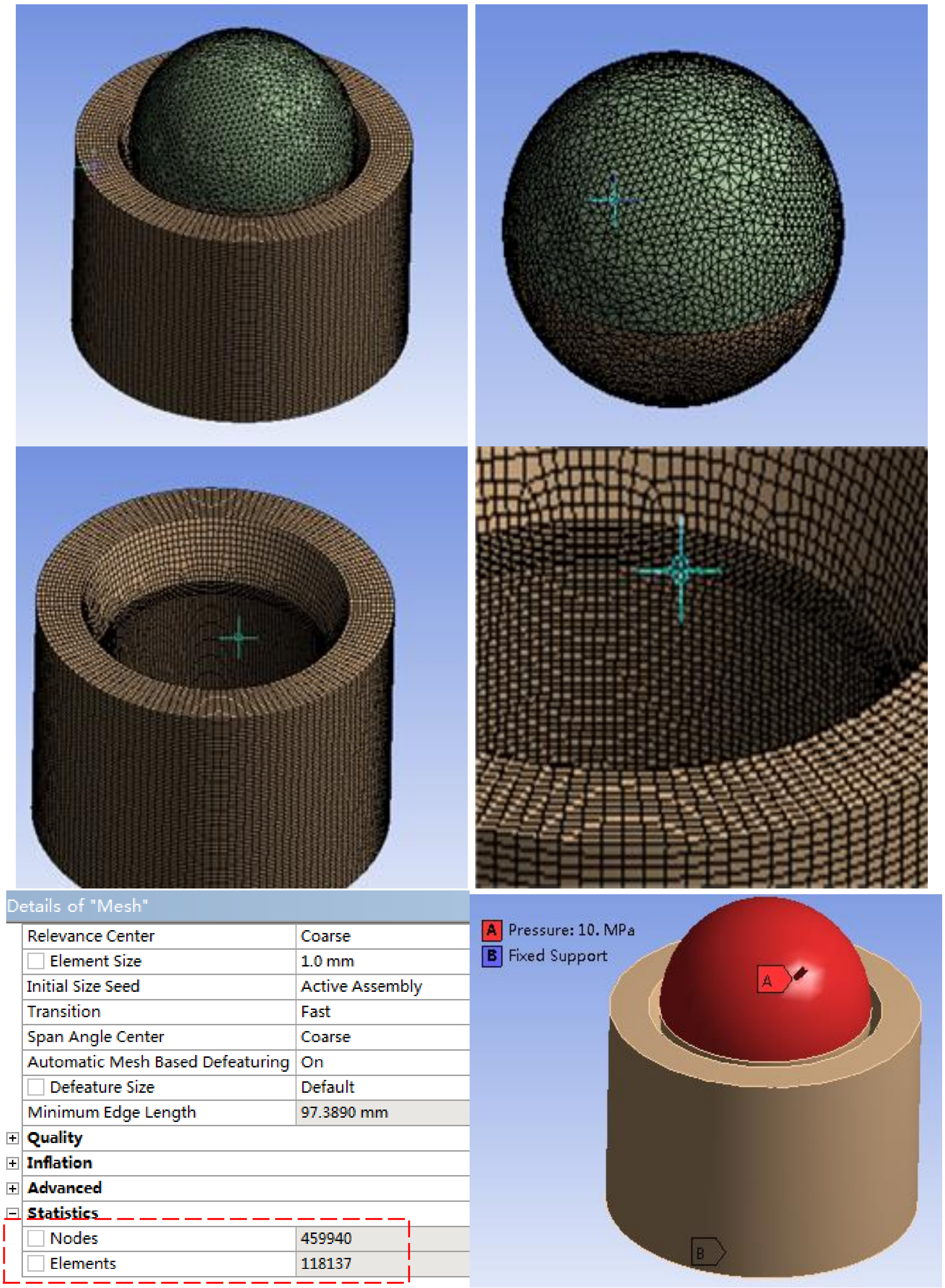


Fig. 7 Load and boundary conditions

Two sets of PGA frac ball pressure capability testing were carried out. The PGA frac ball were placed in a specially designed ball seat. Ball seat material Q235. The actual engineering ball is 0.034m in diameter, as shown in Fig 7. Two groups of specimens were carried out. Remove the possible iron scraps on the ball seat surface to ensure the surface cleanliness. The two balls were coated with lubricating oil to reduce friction, and then one of balls was placed in the middle of the rigid plates which is parallel to universal tester. In order to make the results more accurate, the crosshead speed was limited to1 mm/min. The final result was directly into the computer. In the computer software, the universal tester was loaded to the maximum load value to stop. The testing result was derived, when the unloading is completed. And the above operation was repeated. Because of the large compressive deformation of PGA material, the test results are obtained. The sphere will be stuck in the socket, which is not easy to take out. After removing the sphere, it was found that there was material stickiness between the sphere seat and the sphere. Fig. 19 In order to ensure the cleanliness and tidiness of the socket, another socket is used for compression test to ensure the accuracy of the test. So far, the experiment has been completed.

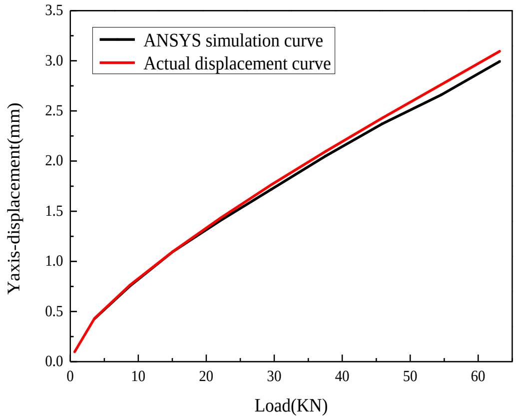


Fig. 8 Relationship diagram of load and Y axis displacement

Fig. 9 Frac ball in seat (after compression)

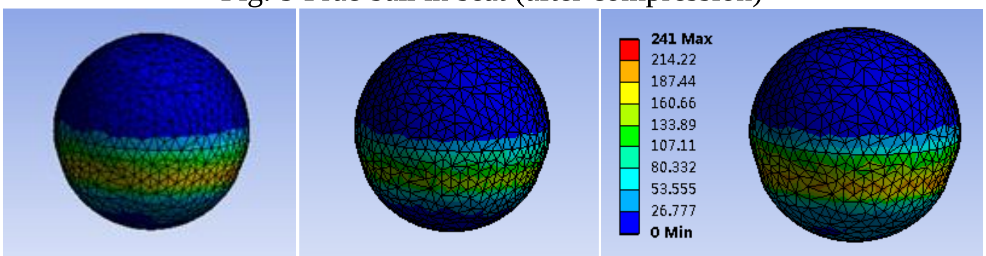


Fig. 10 The MISES stress at the time of 10MPa, 70MPa，100MPa

By comparing the curve results, the maximum error is 3.29%. In general, the error is small. The correctness of the model is verified. The MISES stress at the time of 10MPa and 70MPa is shown in Fig 15. It can be seen that the maximum MISES stress is the roundabout of seat. If the MISES stress is greater than the compressive strength (230MPa), it is considered that the frac ball is destroyed. When the load is 100MPa, the MISES stress of the frac ball reaches the maximum.

The maximum MISES stress position of frac ball is in contact with the sharp corner of seat. The position of deformation and indentation is consistent with test conditions. The iron filings that might appear on the seat surface are removed to ensure the surface cleaning. The ball and seat surface were smeared with lubricating oil to reduce the friction. The crosshead speed is 1mm/min until the machine stops automatically. Due to the large deformation of PGA material, the frac ball was stuck in seat. After removing the ball, it was found that the contact surface was with an indentation. (Fig 12) To ensure that testing ball seat is clean, another ball seat was used.

4. Results and discussion

The FEM model of downhole PGA frac ball-seat was established. By comparing ball-seat pressure capability testing, the correctness of ball-seat FEM model was verified. And by changing angle of cone angle, radius of seat transition and internal diameter difference of ball-seat, the bearing capacity of frac ball with different sizes was studied. The simulation results of ball-seat were obtained. By comparing the result curves, the factors affecting the bearing capacity of PGA frac ball are analyzed.

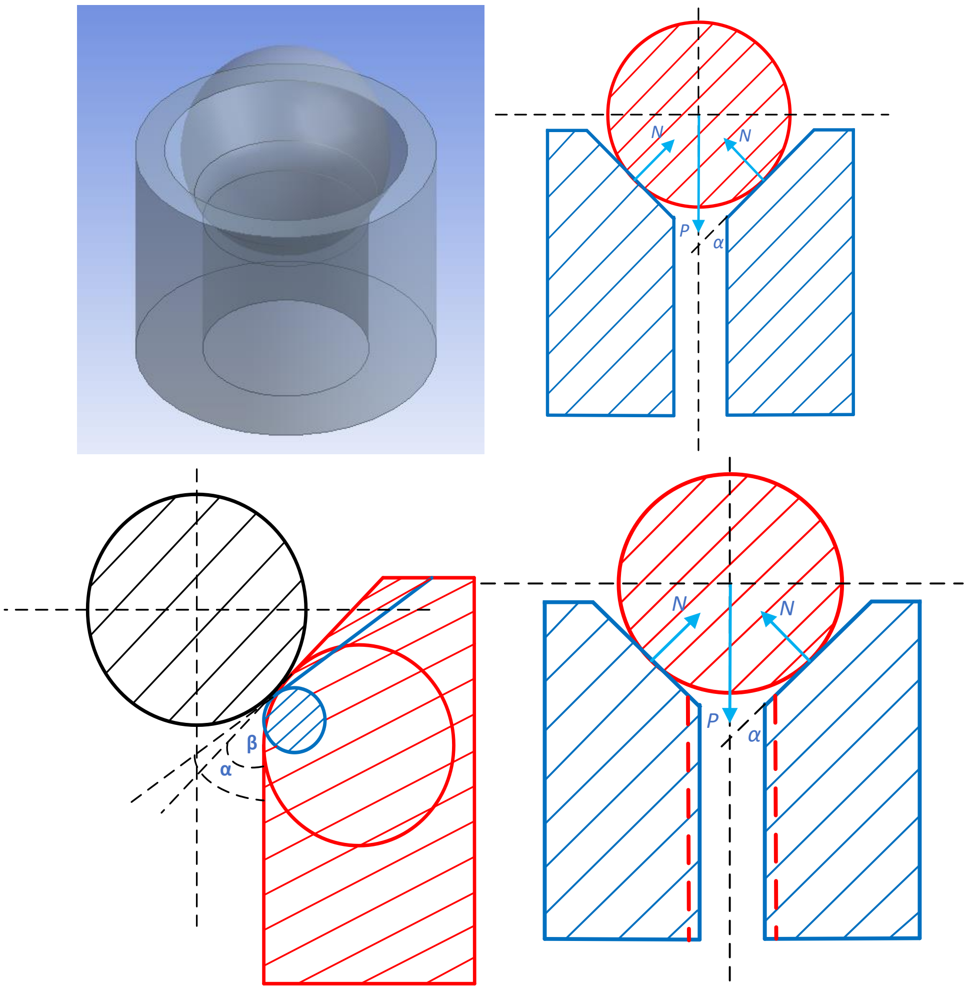


Fig.14 Force diagram of frac ball and seat, Seat with different roundness radius,Different inner diameter of seat

4.1 The effect of angle of cone angle on the bearing capacity

When the load is 50MPa. Internal diameter difference 3mm. The radius of the inverted circle is 10mm. By changing the cone angle of the ball seat, the maximum MISES stress of the PGA frac ball curve is obtained. (Fig.16) The simulation results show that the maximum MISES stress has a process of decreasing first and then increasing.

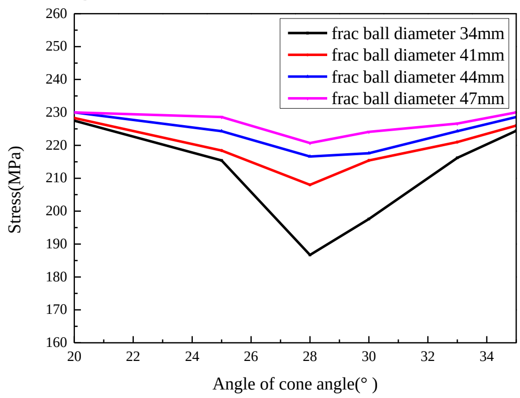


Fig.16 Maximum MISES stress curve of frac ball under different cone angle

When the cone angle is about 28 degrees, the maximum MISES stress of the frac ball is the smallest. With the increase of the diameter of the frac ball, the cone angle has no obvious effect on the bearing capacity of the frac ball.

As the frac ball and seat are coated with lubricating oil, the friction between the frac ball and seat is not considered, as shown in Fig. 25. Because the relative density of frac ball material is 1.2-1.25, the gravity of frac ball can not be considered.

$$P = 2N \sin \alpha \quad (6)$$

$$p = N / S \quad (7)$$

For the metal frac ball, the larger the cone angle is, the smaller the stress of the frac ball is. However, the elastic modulus of PGA frac ball is small and the deformation is large. The pressure depends mainly on the contact area between the frac ball and the ball seat. When the end angle is small, the deformation is small, and the contact area can be regarded as constant. According to Eq 1.7 and 1.8, the pressure at the contact point is very great, and the frac ball is easily stuck in the ball seat. With the increase of the end angle, the pressure will gradually decrease. When the end angle is too large, the frac ball will contact with the sharp part of the ball seat. Because the area of the sharp area is too small, the pressure will increase rapidly.

4.2 The effect of roundness radius on the bearing capacity

When the load is 50MPa. The internal diameter difference is 3mm. The cone angle is 28 degrees. The maximum MISSES stress of PGA frac ball is obtained by changing roundness radius of seat, as shown in Fig 17.

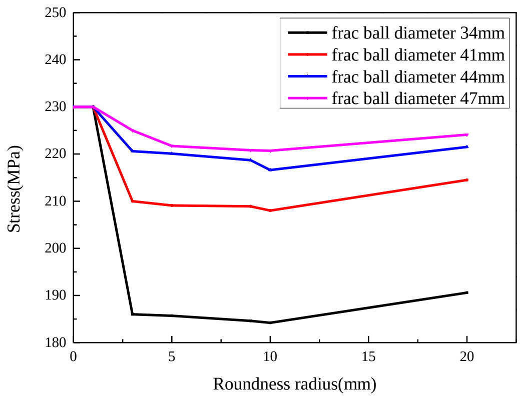


Fig.17 Maximum MISES stress curve of frac ball under roundness radius

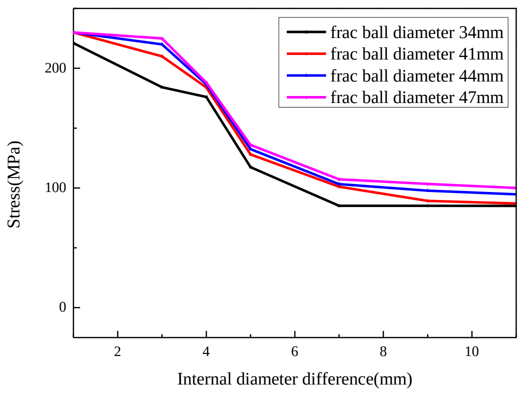


Fig. 18 Maximum MISES stress curve of frac ball under internal diameter difference

The smaller the radius of the roundness is, the greater the maximum MISES stress is. Without considering the roundness, the stress increases sharply and the maximum MISES stress is 230MPa. Moreover, the larger the diameter of the frac ball, the smaller the influence of the radius of the circle on the MISES stress.

If there is no roundness angle in the transitional section corner of seat, Due to the reduction of the contact surface, there is a stress concentration phenomenon, so the rounded corners can increase the contact area and reduce the stress concentration. The excessive radius of the circle causes the frac ball to block the ball seat more easily and cause too much stress.

4.3 The effect of internal diameter difference of frac ball-seat on the bearing capacity

When the load is 50MPa.The cone angle is 28 degrees. The roundness radius is 10 mm. The maximum MISES stress of PGA frac ball is obtained by changing internal diameter difference of frac ball-seat, as shown in Fig 18.

When the difference of inner diameter is small, the maximum MISES stress of frac ball is larger. When the inner diameter difference is increased, the stress increases quickly because of the smaller contact surface. Considering that the reduction of the inner diameter of the ball seat will lead to a reduction in displacement, the difference of inner diameter can be considered as 5mm-7mm.

The most effective way to reduce the pressure is to reduce the inner diameter of seat. When the inner diameter of the small ball seat is reduced, it can ensure that the frac ball is in full contact with the bevel of the ball seat regardless of the deformation of the frac ball. The frac ball will not contact the transition place of the ball seat, and the stress concentration can be avoided completely, and the bearing capacity of the frac ball can be increased well.

5. Conclusion

In this paper, FEM and experiment are combined. The material property data are obtained by pressure capability testing. The simulation is carried out by ABAQUS, and the correctness of the ABAQUS model is verified according to the PGA frac ball pressure capability testing The maximum MISES stress curve of the PGA frac ball is drawn by changing cone angle, roundness radius and inner diameter difference. The bearing capacity of the PGA frac ball under various seat structures is studied, and the reasons for this relationship are analyzed. It provides a reference about improving the bearing capacity of PGA frac ball. The following conclusions are obtained:

1) The bearing capacity of downhole PGA frac ball can be improved by using a new ball seat. When PGA is used to the frac ball, the cone angle of the seat should be 24 degrees -28 degrees.

2) The transition position of the seat greatly affects the bearing capacity of the frac ball. The radius of the transition position can greatly improve the bearing capacity of the frac ball, and the radius of the transition position can be considered 5mm-15mm.

3) The internal diameter difference value of frac ball-seat has the greatest influence on the bearing capacity. However, the decrease of inner diameter will lead to reduction of oil-gas production. The frac ball with the internal diameter difference of 5mm-7mm can be selected by considering the production and the bearing capacity of the frac ball.

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