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Finite element analysis and experimental study on the deformation characteristics of an aluminum alloy fracturing ball

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ABSTRACT

Ball and seat multistage fracturing technology has significantly contributed to the development of oil and gas reservoirs. In this study, a combined finite element analysis (FEA) and experimental method was employed to investigate the deformation characteristics of an aluminum alloy fracturing ball. The distributions of stress, strain, and deformation under different fracturing pressures were investigated. The FEA results showed that the maximum stress, strain, and plastic deformation were generated in the contact region between the fracturing ball and ball seat. Furthermore, experiments were performed to study the pressure-bearing capacity of fracturing ball. The sealing region between the ball and ball seat underwent severe plastic deformation, which indicated that failure is likely to occur. The numerical simulation and experiment results were in agreement. In summary, the fracturing ball demonstrated high-quality sealing performance at pressures exceeding 60 MPa. The risk of failure that might be caused by large deformation was eliminated, and production cost and operation time were reduced.

1. Introduction

Unconventional oil and gas reservoirs that are usually trapped in rocks and are very difficult to extract have received considerable attention in the past decades (Rutqvist et al., 2013; Hossain and Rahman, 2008; Mahrer, 1999). Multistage fracturing technology improves the permeability and production of reservoirs (Hejl et al., 2007; Wozniak, 2010; Finkbeiner et al., 2011). Fracturing tools are designed to fulfill multistage fracturing manipulation. The fracturing ball, which is utilized to seal the ball seat, is the key component in multistage fracturing systems (Daneshy, 2011). During fracturing, the fracturing ball is pumped down the hole to open the sliding sleeve mounted in a specific location. During fracturing, the fracturing fluid with high pressure, high viscosity, and high velocity is injected into the formation from the fracturing tool (Shaw, 2011; Haghshenas and Nasr-El-Din, 2014; Zoveidavianpoor and Gharibi, 2015). When fluid pressure exceeds the rock tensile strength, microcracks form and result in the release of oil and gas reservoirs (Wang et al., 2016; Zheng et al., 2016). Fracturing pressure may have to increase by tens of MPa to achieve this goal. Therefore, the fracturing ball must possess excellent deformation resistance to bear high pressures or it will be deformed and stuck in the ball seat channel (Carrejo et al., 2013; Halvorsen and Arnskov, 2011). For simulation treatment, the fracturing ball has two main functions, namely, activating the sliding sleeve and sealing the zones. Excessive deformation will lead to pressure leakage and cause fracturing failure, both of which increase the production cost and risks involved. Being stuck in the pipeline and colliding with pipeline accessories are some of the risks associated with downhole operation (Zhang et al., 2015).

To avoid excessive deformation, the ball material must have sufficient tensile strength. Fracturing balls generally need to be pumped out when the fracturing process is completed. Therefore, the ball material should possess high tensile strength and low density (Takahashi et al., 2015). Stainless steel and other alloy steels have high tensile strength but are unsuitable for fabricating fracturing balls because of their extremely high densities. By contrast, composite materials with high tensile strength and low density are popular among engineers. According to field data, an increase in ball density hinders backflow from the downhole after simulation treatment. Thus, the fracturing ball material must be selected carefully during design and manufacturing stages.

Several studies have been performed on the fracturing ball and ball seat (Zheng et al., 2015). Carrejo et al. developed a ball and ball seat by using a high-strength corrodible material for horizontal well hydraulic fracturing (Carrejo et al., 2013). Their research

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indicated that a fracturing ball with high-strength corrodible material performs well during fracturing. Baihly et al. conducted a study on the material-mating performance between the ball and ball seat under different pressures (Baihly et al., 2012). Results showed that fracturing balls of different materials fail because of inadequate strength under high pressure. Xu et al. proposed the finite element method to study fracturing balls and ball seats used for horizontal well multistage fracturing (Xu et al., 2012). In their research, balls fabricated with composite materials demonstrate excellent yield strength. They found that the material exerts a significant effect on fracturing ball performance.

Aluminum alloys, which are light metals, have been extensively utilized in various industrial applications, such as automotive, aerospace, and medical industries. Aluminum alloys are highly efficient in heat transfer and pressure resistance and possess higher mechanical strength than conventional metals. In addition, fracturing balls fabricated with aluminum alloys can achieve lower surface roughness via precision machining compared with conventional composite materials. Low surface roughness contributes to good sealing performance. Therefore, aluminum alloys are excellent ball materials when other materials do not satisfy the requirements of high performance.

With the rapid development of finite element technology, numerical simulation method combined with experimentation has been widely used in analysis and design. For example, Finite element analysis (FEA) is the primary tool for design verification and sealing element optimization (Schmidt et al., 2010; Al-Kharusi et al., 2011; Doane et al., 2012; Deng et al., 2013). FEA can be used in contact analysis in oil and gas industries (Podgorbunskikh, 2008; Kuang et al., 2015; Zhu et al., 2015).

However, studies on the deformation characteristics of metal alloy fracturing balls under high pressure are scarce. To understand deformation behavior, an aluminum alloy fracturing ball was investigated in this study. The distributions of deformation, stress, and strain of the fracturing ball and ball seat were investigated. Furthermore, experiments were performed to study the pressure-bearing capacity of the fracturing ball. In summary, this study investigates an aluminum alloy fracturing ball through FEA and experiments. The results provide a reference for the design of new types of fracturing balls.

The rest of this paper is organized as follows. The FEA of the ball and ball seat assembly is developed in Section 2. Subsequently, the obtained results are presented and discussed in Section 3. Finally, main conclusions are briefly presented in Section 4.

2. FEA procedure

2.1. Design principle of the fracturing system

Fig. 1 presents a schematic of the multistage fracturing system

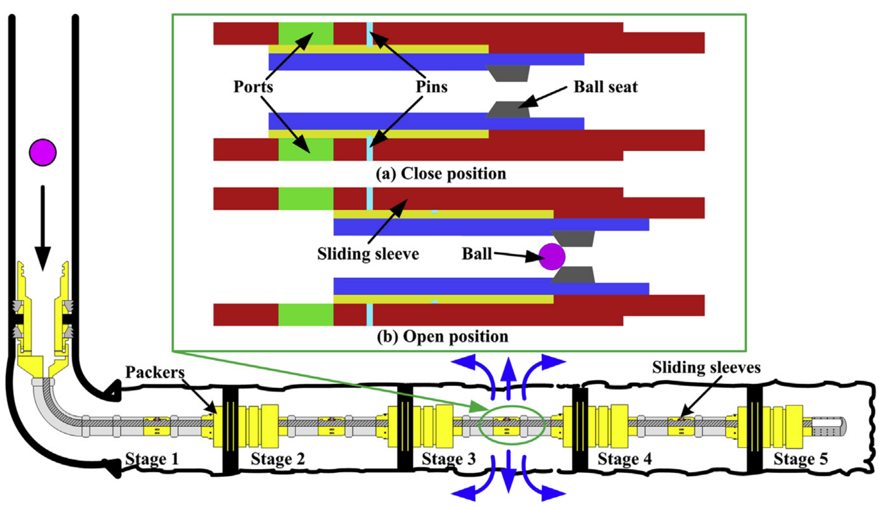

Fig. 1. Schematic of the horizonal multistage fracturing system.

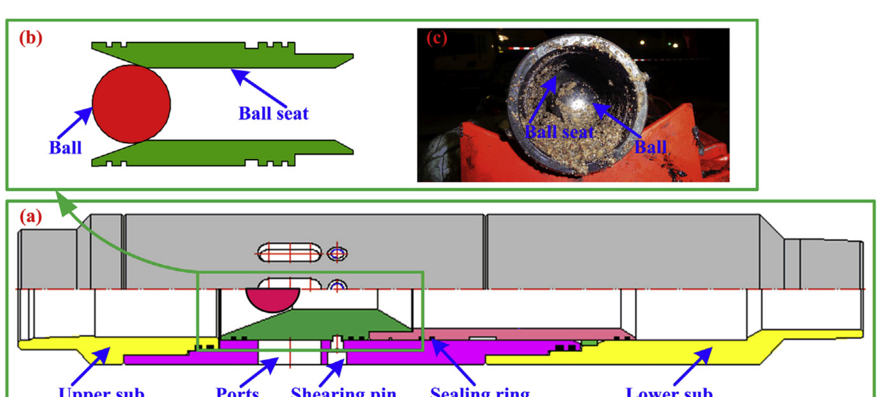

Fig. 2. Structure of the ball drop-activated sliding sleeve.