Study on the abrasion property of the anvil inside a hydraulic DTH hammer fitted with horizontal oriented sliders

Jiang-fu He
State Key Laboratory of Coal Mine Disaster Dynamics and Control, College of Resources and Environmental Science, Chongqing University, Chongqing 400030, China
Post-doctoral Research Station of Mineral Engineering, Chongqing University, Chongqing 400030, China
hejf2016@cqu.edu.cn; http://orcid.org/ 0000-0002-6581-9709

Qi-lei Yin*, Kun Yin
College of Construction Engineering, Jilin University, No. 6 Ximinzhu Str., Chaoyang District, Changchun, 130021,China
yinql_jlu@126.com, yinkun@jlu.edu.cn

ABSTRACT. Hydraulic hammers have been extensively applied to horizontal directional well drilling in hard rock formations. However, the service life of a hydraulic hammer is still unsatisfactory due to the heavy wear or abrasion of the horizontal anvil, which leads to the failure and the reduction of service life in directional well drilling. In order to improve the performance life of a hydraulic hammer, the new type of anvil with a horizontal oriented slider has been designed. The abrasion property of the horizontal oriented slider have been numerically simulated and analyzed by Finite Element Analysis. Simulation and experimental results have shown that the abrasion rate exponentially varies with the mass of the anvil and the friction coefficient of horizontal oriented slider, nevertheless the abrasion rate of horizontal anvil is almost logarithmically varies with moving velocity of oriented slider. The maximum abrasion rate of horizontal oriented sliders will exceed 4% while moving velocity of the horizontal anvil is larger than 3m/s. While the mass of the anvil is 100kg, the maximum abrasion rate of horizontal oriented slider is 7.5‱. However, the maximum abrasion rate of a horizontal oriented slider will be up to 16.5% while the friction coefficient is more than 0.2.

KEYWORDS. Horizontal oriented slider; Hydraulic hammer; Anvil; Abrasion rate; Directional well drilling.

OPEN ACCESS

Citation: He, J.-f., Yin,.Q., Yin, K., Study on the abrasion property of a hydraulic hammer with horizontal oriented sliders, Frattura ed Integrità Strutturale, 42 (2017) 263-271.

Received: 20.05.2017
Accepted: 13.08.2017
Published: 01.10.2017

INTRODUCTION

As a percussive and rotary drilling tool, the hydraulic DTH hammer with a fluidic amplifier has been extensively applied to geological core drilling, hydrological well drilling, trenchless drilling, oil and gas well drilling [1, 2]. due to the high penetration rate, low occurrence of drilling accidents and excellent borehole quality in drilling, the hydraulic hammer with a fluidic amplifier has also been regarded as the most efficient drilling tool in hard rock or complicated formations [3-5]. With the rapid development of drilling technology, the application of hydraulic hammers with a fluidic amplifier has been extended to horizontal directional well drilling in recent years, which contributes to the development of trenchless drilling technology of oil-gas pipeline construction in hard rock and complicated formations. Unlike the conventional vertical hole drilling with hydraulic hammers, horizontal directional well drilling demands the anvil horizontally impact the drill bit while the hydraulic DTH hammer is in operation, which aggravates the abrasion of hydraulic hammer and leads to the reduction of service life of hydraulic DTH hammers.

In order to improve the penetration rate and drilling cost of hard rock formations, the hydraulic hammer has been initially proposed and designed in Former Soviet Union, and a proven efficiency of 40% has been achieved with new generation of hydraulic hammer. Afterwards, Yuri and Andrei conducted relevant field tests to improve the efficiency of the hammer in US, which leads to the development of hydraulic hammer [6]. Allowing for the cost reduction and technological advantages in deep or medium-to-hard rock formations, D. Pixton and D. Hall have proposed the advanced mud hammer system, and the prototype of the hammer system have also been developed and reported [7]. However, no extra introduction of this mud-actuated hammer has been reported with respect to the field application results and service life time. Therefore, the new type of hydraulic DTH hammer with a horizontal oriented slider has been urgently designed and applied to horizontal directional well drilling in order to improve the service life of hydraulic DTH hammers. Moreover, the abrasion property of hydraulic DTH hammers with horizontal oriented sliders should be intensively studied with respect to the application of hydraulic DTH hammers to horizontal directional well drilling.

While in horizontal directional well drilling with hydraulic DTH hammers, the piston is actuated by powered muds, which drives the hammers horizontally and reciprocally impact the drill bit. However, the service life of hydraulic DTH hammers is unsatisfactory due to the reciprocating motion of anvil with high frequency, which deteriorates the performance of hydraulic DTH hammers in horizontal directional oil-gas well drilling [8]. In order to improve the service life of hydraulic DTH hammers in horizontal directional well drilling, a specialized anvil with horizontal oriented sliders has been designed, as shown in Fig. 1. The material of slider has been optimized, and totally 6 sliders are embedded into the anvil, which contributes to reducing the abrasion of hydraulic DTH hammer. Furthermore, the abrasion property of horizontal oriented slider has numerically analyzed by Finite Element Analysis, which indicates the design and optimization of hydraulic hammers in horizontal directional well drilling.

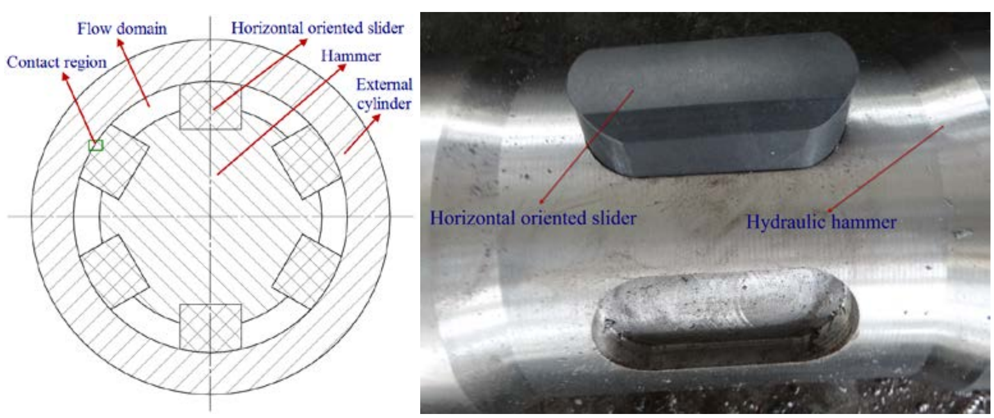

Figure 1: Structure of hydraulic DTH hammers with horizontal oriented slider.

In previous studies, the service life of a hydraulic DTH hammer has been analyzed by drilling crews and researchers while in vertical or up-down drilling. C.W. Li has analyzed the effect of material property of hydraulic hammer on its service life time in 2002, and numerical models of damage mechanism are established [9]. Ding Daipo has improved the service life of hydraulic DTH hammers up to 120h while in oil-gas well drilling [10]. Meanwhile, series of experiments on abrasion property of hydraulic DTH hammers in vertical well drilling have been conducted by He Liu in 2014 on the basis of Finite Element Analysis (FEA), which numerically and practically contributes to improving the service life of hydraulic DTH hammers [4]. In addition, the abrasion process of abrasive particle is numerically analyzed by Wu Jinghua et al., which could theoretically illustrate the behavior of abrasive impacting [11]. Furthermore, Li Weitao has optimized the hydraulic DTH hammer by numerical analysis on the fluidic amplifier in order to improve the service life of hydraulic DTH hammers [10]. Some other related work has been finished with different experiments and apparatus in order to improve the service life of hydraulic hammers in various drilling conditions [13, 14].

However, there are no corresponding researches on the improvement of service life of hydraulic DTH hammer in horizontal directional well drilling since the numerical modelling technique in drilling engineering has been popularized throughout the world [15]. In addition, no new type of hydraulic hammer with anti-abrasive slider has been existed in horizontal directional well drilling or trenchless drilling. Thus, the research on anti-abrasive property of hydraulic DTH hammers should be conducted in order to improve the service life of hydraulic hammers while in horizontal directional well drilling.

The study of hydraulic DTH hammers on the abrasion property of a horizontal oriented slider is an efficient way to improve the service life time of hydraulic hammers, including numerical simulation and experimental analysis. In this paper, numerical models of the anvil inside hydraulic DTH hammers have been developed with several groups of oriented sliders, and different friction coefficients (different material of oriented slider) of horizontal oriented sliders, various mass and moving velocity of the anvil have been denoted as the variables in FEA simulation. In end, the abrasion rate of oriented slider in hydraulic hammers has been obtained by FEA, which promotes the improvement of service life time of hydraulic hammers with a horizontal oriented slider while in directional well drilling.

METHODOLOGY AND ABRASION THEORY

Unlike vertical well drilling or up-down well drilling, the working principle of hydraulic DTH hammers with oriented sliders in horizontal directional well drilling is distinguished. Meanwhile, the abrasion theory of oriented sliders has also been presented.

Working principle of hydraulic hammers with horizontal oriented slider

While drilling a horizontal directional well with a hydraulic DTH hammer, the operation principle of the hydraulic hammer with horizontal oriented sliders is shown as Fig 2.

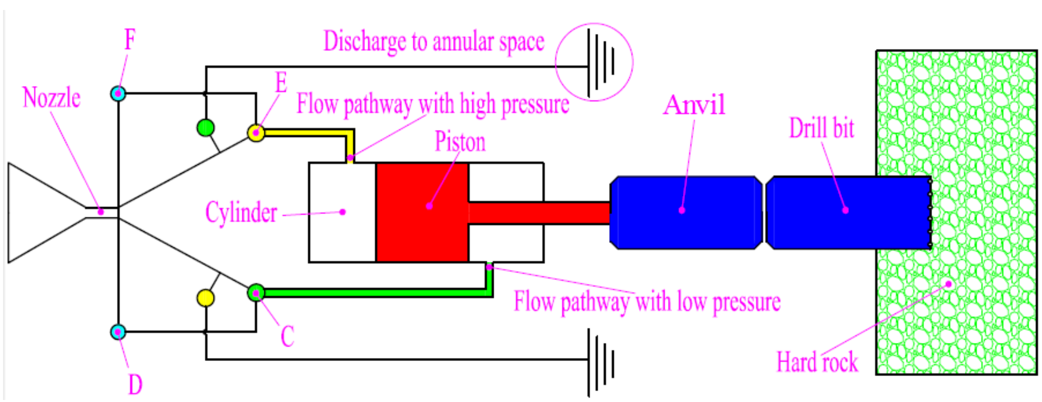

Figure 2: Schematic diagram of a hydraulic hammer with the horizontal anvil. C, E: Discharge channel; D, F: Controlled flow channel

The pumped mud with high pressure and velocity was initially delivered to the nozzle through the drilling pipe, which is termed as the pressure inlet. Then the mud is sprayed by the nozzle to generate a wall-attachment effect with high mud speed. It has been provided that the mud is attached to the back chamber (as shown in yellow pipe line), thus the piston then is actuated by high pressure mud to horizontally impact the drill bit. In the meantime, the controlled channel F is stimulated by a pressure pulse while the piston with the anvil moves to the right dead point, simultaneously the discharge channel of high pressure mud is shifted from channel E to channel C, and the mud is instantaneously pumped into the ante-chamber of the cylinder (as shown in green pipe line), which actuates the piston to move back to return strokes. The whole working process of the hydraulic hammer rapidly and periodically completes in hundreds of a second. Therefore, the reciprocating impact energy transmission can be obtained by the periodic exchange of pumped mud in ante-chamber and back chamber.

In addition, the circulating mud in back chamber and ante-chamber will be discharged through the channel C and channel E, which is termed as the pressure outlet. Then it will be discharged to the annular space between the cylinder and drilling pipes.

Abrasion theory

The complete abrasion theory was proposed by Archard, and was optimized by Rowe in 1995 [16-18]. While the hydraulic DTH hammer is operated in horizontal directional well drilling, the oriented slider is reciprocally abraded by external cylinder with high frequency. The volumetric wearing capacity V can be derived from Eq. 1, which is closely related to the friction coefficient, lubrication coefficient and the load.

$$V = k_m \beta (1 + \alpha \mu^2) \frac{WL}{H} \tag{1}$$

Where, k_m, α denotes the constant, dimensionless; β denotes the lubrication coefficient, dimensionless; μ denotes the friction coefficient, dimensionless; W denotes the applied load of oriented slider, MPa, and H denotes the Brinell Hardness, HBW.

The formula of abrasion theory is feasible to the wear of horizontal oriented sliders, thus the friction coefficient, applied load and the moving velocity of oriented slider were employed as the variables while in the simulation of abrasion property of the anvil with horizontal oriented slider.

FEA SIMULATION

There are totally 3 variables used in the simulation, which are friction coefficient, moving velocity and applied load, respectively. Each variable has at least 5 models in numerical simulation. In order to obtain the abrasion rate of the anvil inside hydraulic DTH hammers with horizontal oriented slider, the numerical modelling, meshing and solving process are successfully completed.

Numerical Modelling and Meshing

As shown in Fig. 3, the numerical model of the anvil with oriented sliders was developed by software ANSYS 2014 according to the parameter of a 203mm hydraulic DTH hammer. The material models of external cylinder and oriented slider were defined as 35CrMo and Teflon with carbon fiber, respectively.

There are totally 6 horizontal oriented sliders are evenly distributed along the outer circle of the anvil, and the parameter of oriented slider is $80mm \times 36mm$. In end, 3 groups of material models are established in whole, as shown in Tab. 1.

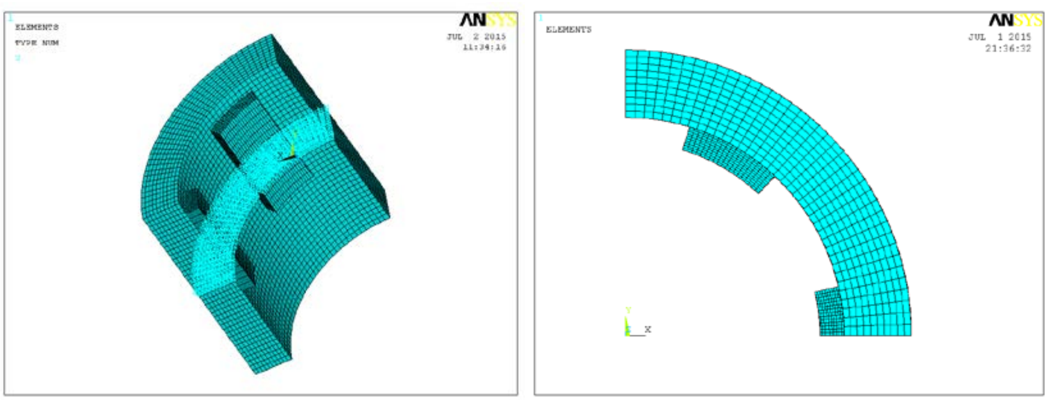

Figure 3: Numerical model and meshes of a hydraulic DTH hammer with horizontal oriented sliders.

The numerical model was quarterly symmetric in order to reduce the computational time. In addition, the deformation of oriented slider and external cylinder is defined as plane strain problem. The numerical model was meshed with 3D structure cell SOLID 185, and the contact cells between oriented slider and external cylinder are defined as Contact 174. Furthermore, the grids of contact region should be refined, which contributes to the improvement of simulation results. Thus the grids type of contact region was defined as surface-to-surface contact, which is termed as Target 170 in ANSYS, as shown in Fig. 4. The cells of horizontal oriented slider are in red, and the cells of external cylinder are in blue.

Materials (slider/External cylinder)	Applied load (MPa)	Friction coefficient (m/s)	Temperature (C°)
35CrMo/PTFE	50 ~ 70	0.01 ~ 0.03	-180 ~ 250
35CrMo/POM	50 ~ 70	0.15 ~ 0.35	-180 ~ 260
35CrMo/P-Ni	0 ~ 715	0.1	-180 ~ 200

Table 1: Property of numerical models of hydraulic hammers with horizontal oriented sliders.

There are totally 42318 elements in each of numerical model, and the meshed grids are hexahedrons, which are obtained by sweep meshing of ANSYS. All of the meshed grids are volume grids with a maximum diameter of 3mm, and the grid coordination is excellent. The maximum grid deviation is 5%, which guarantees the accuracy of simulation results. The meshed elements of a horizontal oriented slider are shown as Fig. 3.

Boundary Conditions and Solver Settings

In order to reduce the computational time, the numerical model was simplified with horizontal friction force, and other extra loads were ignored, such as hydraulic pressure, fluids resistance and buoyance of drilling mud. Moreover, the boundary condition of contact region between horizontal oriented slider and external cylinder is simplified as wetting boundary conditions. In addition, the initial load on oriented sliders was applied with 1kN, and friction coefficient between oriented slider and external cylinder is denoted as 0.02. Once all numerical models were finishing computing, the abrasion rate of hydraulic hammer has been obtained, which is helpful to optimize the structure design of hydraulic DTH hammers with horizontal oriented sliders.

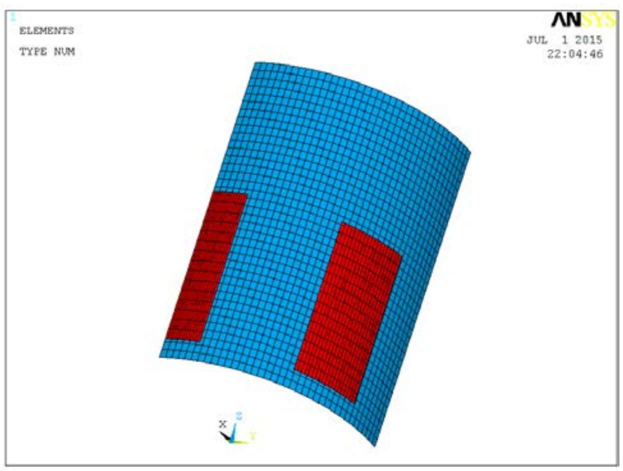

Figure 4: Contact cells between horizontal oriented slider and external cylinder.

With regard to the solver settings of numerical simulation with horizontal oriented sliders, there are totally 1000 time steps were set. The details of solver settings are as shown in Tab. 2. Thus the abrasion property of hydraulic hammers with horizontal oriented sliders can be obtained with various material models and boundary conditions.

RESULTS AND DISCUSSIONS

The abrasion property of a hydraulic hammer with horizontal oriented sliders has been numerically modeled by FEA simulation. Especially the moving velocity of the anvil, the mass of anvil or applied load, and the friction coefficient of horizontal oriented sliders have been separately analyzed with various numerical models. Meanwhile, the related experiments are conducted in order to improve the service life of hydraulic DTH hammers while in horizontal directional well drilling. In end, the abrasion rate of hydraulic hammer with horizontal oriented sliders is obtained, and the abrasion property of horizontal oriented sliders is discussed according to numerical simulation results.

Meshes No.	42318
Friction Coefficient	0.02
Applied loads (kN)	1
Total Steps	1000
Time Step	2
Convergence Coefficient	0.5
Moving Velocity of Hammer (m/s)	3

Table 2: Details of boundary condition and solver settings.

Effects of hammer mass on abrasion property of hydraulic hammer with oriented sliders

As shown in Fig. 5, the Von-Mises stress of oriented sliders has been obtained. While the mass of the anvil is 60kg, the main stress of oriented sliders is approximately 6MPa. It can be implied that the main stress of horizontal oriented sliders is nearly linearly increasing with the raise of anvil mass. While the mass of the anvil exceeds 100kg, the main stress of oriented sliders will exceed 9MPa, which will reduce the working performance of hydraulic hammer with horizontal oriented sliders. Thus the abrasion between horizontal oriented sliders and external cylinder has been increased while the applied stress of oriented sliders is increasing. Therefore, the mass of anvil should be less than 100kg while in horizontal directional well drilling with hydraulic hammer, which contributes to improvement and optimization on the design of hydraulic hammer with horizontal oriented sliders.

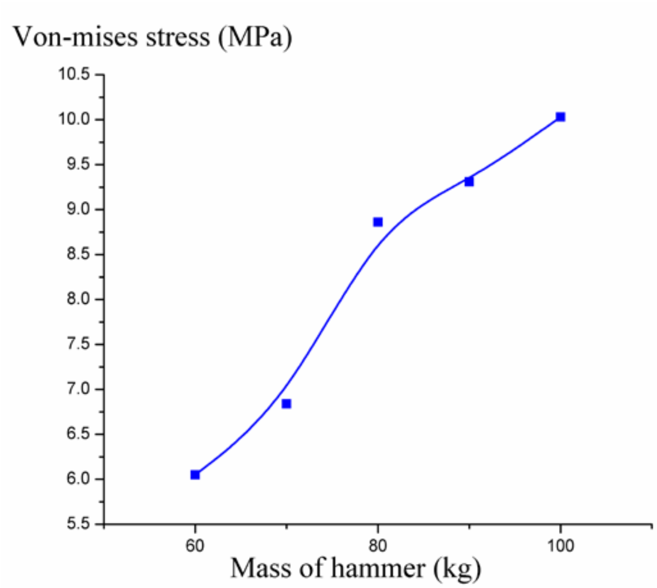

Figure 5: Effect of anvil mass on the Von-Mises stress of hydraulic hammer with horizontal oriented sliders.

Meanwhile, the variation of anvil mass on the abrasion property of hydraulic hammer with horizontal oriented sliders is shown as Fig. 6. The lighter the impact hammer is, the abrasion rate of oriented sliders will be, and the service life of hydraulic hammer with horizontal oriented sliders will be longer. It can be concluded that the abrasion rate of oriented sliders is approximately exponentially increasing the augment of hammer mass. The maximum abrasion rate of horizontal oriented sliders is 7.5‱, which meets the requirements of impact energy of hydraulic hammer while in horizontal directional well drilling. In addition, the maximum abrasion rate deviation of horizontal oriented sliders with various mass of anvil is less than 1‱, thus the effects of anvil mass on the abrasion property of the hydraulic hammer is acceptable.

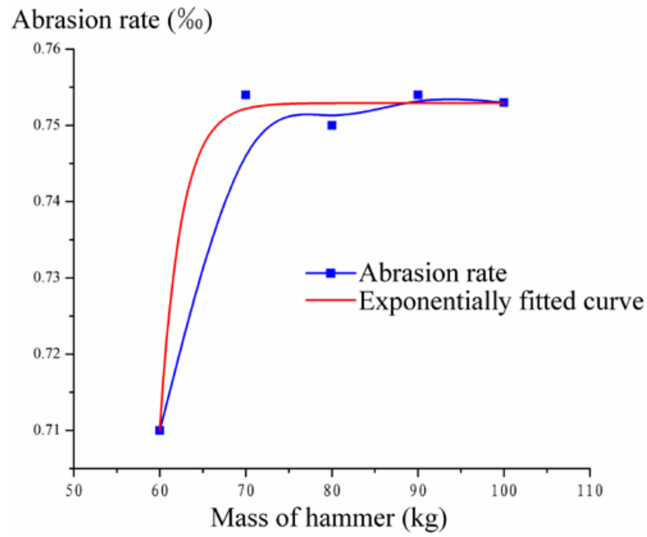

Figure 6: Variation of anvil mass on the abrasion property of hydraulic hammer with horizontal oriented sliders.

Effects of Moving Velocity of the Anvil on Abrasion Property of Horizontal Oriented Sliders

As shown is Fig. 7, the abrasion property of a horizontal oriented slider is affected by the moving velocity of the anvil, which is corresponding to the specification of impact energy of hydraulic hammer. It can be concluded that the abrasion rate of a hydraulic hammer with horizontal oriented sliders is almost logarithmically varies with the moving velocity of the anvil. While the moving velocity of the anvil and horizontal oriented slider is 1m/s, the minimum abrasion rate of oriented slider is nearly 1.8%. The abrasion rate of horizontal oriented slider sharply varies with the increase of moving velocity. While the moving velocity of the anvil and oriented slider exceeds 3m/s, the maximum abrasion rate of horizontal oriented sliders will be up to 4%, which would have a significant effect on the service life of hydraulic hammers with horizontal oriented sliders.

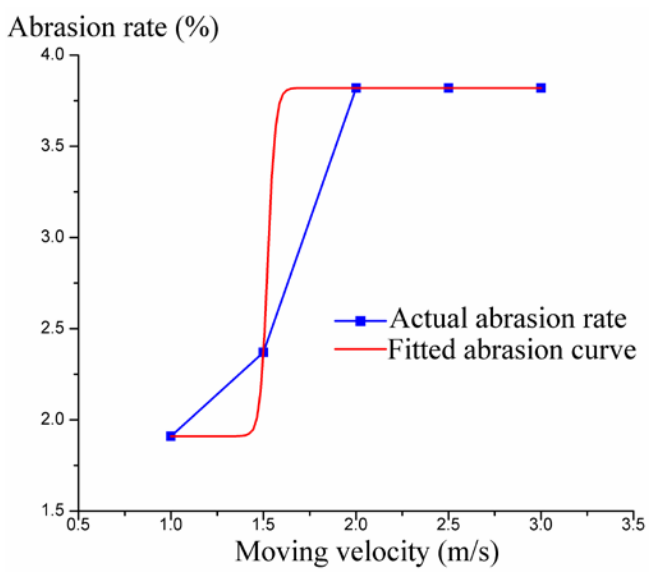

Figure 7: Variation of moving velocity on the abrasion property of hydraulic hammer with horizontal oriented sliders.

The actual simulation results are slightly different with the fitted abrasion rates. The maximum deviation between simulation results and the logarithmically fitted abrasion rate is less than 2%, which is tolerable in real time operation of hydraulic hammers with horizontal oriented sliders. Meanwhile, the abrasion rate of horizontal oriented sliders is smaller,

the longer service life of the hydraulic hammer will be. In order to improve the service life of hydraulic hammer with horizontal oriented sliders, the moving velocity of the anvil should be less than 4m/s, thus the abrasion rate of oriented sliders in horizontal directional or vertical well drilling is acceptable.
According to the filed application results of the hydraulic hammer with horizontal oriented sliders, the abrasion of the anvil inside the hydraulic hammer will be dramatically aggravated while the moving velocity of the anvil exceeds 3m/s [19]. Thereby the simulation results have shown extraordinary agreements with the actual cases of hydraulic hammer in directional well drilling. It can be suggested that the moving velocity of the anvil with horizontal oriented sliders should be significantly controlled in horizontal directional well drilling, which contributes to the improvement of service life of hydraulic hammer with horizontal oriented sliders.

Effects of Friction Coefficient on the Abrasion Property of Horizontal Oriented Sliders

The effect of friction coefficient of the anvil on abrasion rate of horizontal oriented slider has been numerically analyzed by FEA method. As shown in Fig. 8, it can be concluded that abrasion rate of oriented sliders is approximately exponentially increases with the friction coefficient of oriented sliders. While the friction coefficient between oriented sliders and external cylinder exceeds 0.2, the maximum abrasion rate of oriented slider will be up to 16.5%, which seriously reduce the service life of hydraulic hammers in horizontal directional well drilling. While the friction coefficient of horizontal oriented sliders is less than 0.05, the minimum abrasion rate of oriented sliders is much more considerable. Therefore the design of hydraulic hammers with oriented sliders is qualified due to the friction coefficient of PTFE with carbon fiber is 0.02.

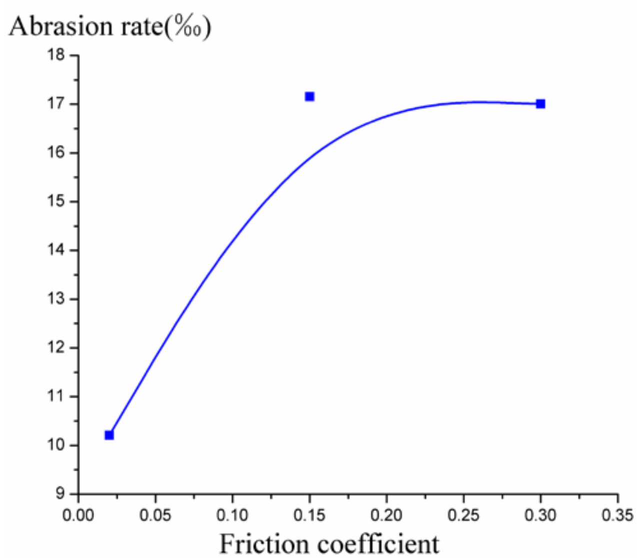

Figure 8: Variation of friction coefficient on the abrasion property of hydraulic hammer with horizontal oriented sliders.

The service life of hydraulic hammers is severely influenced by friction coefficient of oriented sliders in horizontal directional well drilling. Once the horizontal oriented sliders are abraded, the horizontal alignment among piston, the anvil and oriented sliders will be damaged, which will lead to the failure of hydraulic hammer with oriented sliders in horizontal direction well drilling. Thereby the friction coefficient of horizontal oriented sliders must be controlled in order to reduce the abrasion rate of hydraulic hammer with horizontal oriented sliders. Conclusions have been drawn that the friction coefficient of oriented sliders should be less than 0.2 in order to improve the service life of the hydraulic hammer with oriented sliders in horizontal directional well drilling.

CONCLUSIONS

1) Hydraulic hammer with horizontal oriented sliders have been designed, and corresponding numerical models have been developed to investigate the effects of anvil mass, friction coefficient and moving velocity of the anvil on abrasion rate of oriented sliders.

2) The maximum abrasion rate of horizontal oriented sliders is 7.5‱ while the anvil mass is 100kg, otherwise the abrasion rate will be up to 4% while the moving velocity of the anvil inside hydraulic hammers exceeds 3m/s.
3) The service life of hydraulic hammers is severely influenced by friction coefficient of horizontal oriented sliders, and the friction coefficient must be less than 0.2 while in horizontal directional well drilling.
4) New type of hydraulic hammer with oriented sliders is qualified in horizontal directional well drilling, which contributes to the improvement on service life of hydraulic DTH hammers.

ACKNOWLEDGMENTS

The authors thank to the supports from the Project funded by China Postdoctoral Science Foundation (Project NO. 2017M612916) and the China Pipeline Research Institute of CNPC, China Petroleum Natural Gas Pipeline Bureau (Project NO. 2014220101001321), which are gratefully acknowledged. The authors also express their thanks to Hou-ping Liu and Yanli Liu for their precious help.

REFERENCES

[1] Yin, K., Wang, M, et al., Percussive and Rotary Drilling, Geological Publishing Press, Beijing, (2010).
[2] Li, S.-Z., Drilling and Exploring Technology, Geological Publishing Press, Beijing, (1989).
[3] Han, G., Bruno, M., Lao, K., Percussion drilling in oil industry: review and rock failure modeling, The AADE national technical conference and exhibition, Houston, USA, (2005).
[4] Liu, H., Yin, K., Peng, J.M., Yin, Q.L., Fracture failure analysis of baseplates in a fluidic amplifier made of WC-11Co cemented carbide, rattura ed Integrità Strutturale, 27 (2014) 53-65.
[5] Melamed, Y., Kiselev, A., Gelfgat, M., Dreesen, D., Blacic, J., Hydraulic hammer drilling technology: developments and capabilities, J. Energ. Resour. Technol., 122(1) (2000) 1-8.
[6] Melamed, Y., Kiselev, A., Gelfgat, M., et. al., Hydraulic Hammer Drilling Technology: Developments and Capabilities. Journal of Energy Resources Technology, 122(01) (2003).
[7] Pixton, D., Hall, D., Advanced mud hammer system. Novatec. Inc. 2185 South Larsen Parkway, Provo, UT.
[8] He, J., Zhao, X., Kun, Y. et al., Application of a fluidic amplifier to horizontal directional well drilling. Asia-Pacific energy equipment engineering research conference, Atlantis Press, 60-63 (2015).
[9] Chuanwu, L., Fadong, L., Hai, R. J., Applications of Hydraulic Operated Hammers in Pilot Hole Drilling of Kezuan-1 Well, Petroleum Drilling Techniques, 30(5) (2002).
[10] Daipo, D., Research on the working life of key accessory of oil drilling impacting machine, Master thesis, Jilin University, (2008).
[11] Jinghua, W., Wencheng, T., Liyi, Z., Numerical analysis of impacting behavior of abrasive particle, Machine Tool and Hydraulics, 36(9) (2008) 2-77.
[12] Weitao, L., The experiment and research on the working life of the liquid jet amplifier of the hydraulic hammer, Master thesis, Jilin University, (2004).
[13] Qingyan, W., Kun, Y., et al., Development and application of hydrokinetic hammer's simulation technique, Petroleum Drilling Technique, 36(1) (2008) 45-49.
[14] Tesar, V., Hung, C.-H., Zimmerman, W. B., No-moving-part hybrid-synthetic actuator, Sensors and Actuators A: Physical, 125 (2006) 159-169.
[15] Xingkun, G., Zhengyi, S., Hongxuan, L., Application and prospect of computer simulation technique in drilling engineering, (2007) 118-121.
[16] Ting, J., Huaping, Y., Hui, Y., Numerical simulation of the process of friction and wear, Lubrication Engineering, 38(12) (2013) 88-92.
[17] Huaisong, C., Study of numerical simulation on reciprocating wear under boundary lubrication condition, Master's theses, Technical University of Wuhan, (2005).
[18] Zhongyong, G., Wubin, X., et al., Experimental study and analysis of wear and abrasion of rails, Steel, 37(8) (2002) 53-57.
[19] He, J., Theoretical and Experimental Research on Hydraulic Hammer with Application to Horizontal Directional Well Drilling in Hard Rocks, Thesis, Jilin University, China, (2016).