Dynamic Impact Damage of Oil and Gas Pipelines

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Abstract. Dynamic impact damage is one of the main causes of Oil and Gas pipeline failure, but there is no systematic research method and achievement on pipeline dynamic impact damage at present. As the weak link of pipeline, girth weld is the most important research object in practical engineering application, so it is urgent to study the damage behaviour of pipeline girth weld under dynamic impact load. This paper reviews the experimental technology of split Hopkinson Pressure Bar in the field of dynamic impact mechanics, the theoretical knowledge of stress wave propagation theory, dynamic mechanics and damage mechanics, as well as the finite element simulation analysis method, explains the application of theory and technology in practical engineering, introduces the research status of mechanical behaviour of pipeline girth weld under dynamic impact load, and looks forward to the theoretical and technical trend of dynamic impact mechanics of pipeline girth weld. It lays a foundation for the dynamic impact safety evaluation and the establishment of protection system of pipeline girth weld.

1. Introduction

Girth weld is an indispensable part of pipeline construction[1]. Long distance oil and gas pipeline is connected by girth weld, and the pipeline is connected by girth weld in the station. The toughness of girth weld material is poor, and it is easy to break and fail, which becomes the weak link of oil and gas pipeline. After a long period of service, there are countless cases of oil and gas pipeline failure caused by weld defects. For example, according to the statistics of the U.S. Pipeline Safety Office[2], between 1985 and 1996, the failure rates of dangerous liquid pipelines and natural gas pipelines due to weld problems accounted for 12% and 8%, respectively.

In many cases, the structure and material of oil and gas pipeline bear the action of explosion and impact load[3], such as the impact of third party construction, the impact of falling stone, the shock wave load caused by pipeline explosion, the dynamic load caused by the sudden change of ground load, the hull impact load of offshore pipeline and the impact load caused by earthquake, and so on. Their common characteristics are that the pipeline material and structure bear the action of transient strong impact load and experience large elastic and even plastic deformation at high deformation rate[4]. Different from the static load, the dynamic impact load will produce stress wave in the pipeline material and structure and propagate along the pipeline. Therefore, the damage caused by the dynamic impact load is often the weak part of the loading point at a certain distance. Girth weld is the weak part of pipeline, so when the pipeline is subjected to impact load, it is often damaged at the girth
weld. In order to design the impact protection of pipeline structure, it is necessary to fully understand and master the dynamic impact mechanical behavior of pipeline girth weld[5]. Therefore, the study of damage evolution mechanism and failure prediction of pipeline girth welds under dynamic impact load is a key problem to be solved in the field of safety evaluation and protection of oil and gas pipelines at present.

At present, the research on pipeline safety basically adopts quasi-static research theory and experimental technology[6], the research on high strain rate damage of pipeline structure is very few, and there is no systematic research method and results. At present, pipeline research only uses Charpy impact test (CVN), drop hammer tear test (DWTT), and fracture toughness test (KIC, CTOD, J integral) to qualitatively measure and characterize the ability of materials to resist fracture. However, the field of dynamic mechanics has developed mature theoretical basis (such as stress wave theory, dynamic fracture mechanics and damage mechanics)[7]. Experimental techniques (such as split Hopkinson Pressure Bar experimental technique for measuring stress-strain relationship and fracture strain at high strain rate) and finite element analysis (structural dynamic analysis module of simulation software such as ABAQUS, ANSYS) have not yet been introduced into the study of dynamic impact damage of pipeline[8], and the girth weld itself is an uneven material, which makes the quantitative study of dynamic impact damage of pipeline blank for a long time.

In this paper, the present situation of dynamic impact damage of girth welding joints in the world is summarized, the necessity of studying the dynamic damage mechanism of girth welding joints is analyzed, the experimental and theoretical results in the field of dynamic mechanics of materials and structures are summarized, and the history and application status of separated Hopkinson bar experimental technology are reviewed. Combined with the problem of dynamic impact damage faced by national pipeline safety and economy at present, the theory and experimental technology developed in the field of dynamic mechanics of materials and structures are introduced into the study of dynamic impact damage mechanism of pipeline girth welds. The stress wave propagation theory, dynamic fracture mechanics and damage mechanics theory are used, combined with the structural dynamic analysis module in finite element simulation software. It is of great engineering significance and application value to study the damage mechanism and evolution law of pipeline girth weld under dynamic impact load, which provides a certain reference for the study of dynamic mechanics of pipeline.

2. Development Status of Dynamic Mechanics

At present, in the field of material science, the split Hopkinson Pressure Bar (SHPB) technology is the most widely used in measuring the dynamic mechanical properties of materials [13]. The typical split Hopkinson Pressure Bar device is shown in Fig. 1. The basic principle is that the short sample is placed between two compression bars, and the acceleration wave is generated by accelerating mass block, short bar impact or explosion, and the sample is loaded. At the same time, the wave signal is recorded by a strain gauge pasted on the compression bar and a certain distance from the end of the bar. If the compression bar remains elastic, the wave in the bar will propagate at the elastic wave velocity without dispersion. Based on the one-dimensional stress wave theory, the stress, strain and strain rate history in the specimen can be deduced by using the incident wave, the reflection wave and the transmission wave measured by the strain gauge pasted to the compression bars.

Hopkinson bar experimental technology was originally only used to measure the dynamic mechanical properties of ductile materials such as metals. Later, some scholars extended its testing technology to brittle materials [14], such as large diameter Hopkinson bars used to test rock mechanical properties, and some scholars developed nylon Hopkinson bars for testing soft materials [15]. Nowadays, Hopkinson bar has become one of the most widely used and mature technologies in the testing of dynamic mechanical properties of materials.

Hopkinson bar experimental technology has been more and more used in the dynamic mechanical design and protection of structures, and a lot of practical engineering applications have been made. Hopkinson pressure bar has made good progress in the study of spallation of concrete: Klepaezko [16] has used Hopkinson bar experimental technology to measure the spallation strength of a concrete, and Rubio [17] has also used similar technology to study the spallation strength of ceramic materials. Hu
Shisheng [18] et al proposed that the spallation strength of concrete materials be studied by using large diameter Hopkinson compression bar and patch on the specimen, and better results have been obtained. The high G value accelerometer is mostly used to measure the impact load in the process of penetration and armour piercing. Because the usual calibration equipment can not produce a very high acceleration value, it is impossible to calibrate the acceleration sensor with high G value. In foreign countries, Hopkinson pressure bar technology has been applied to the calibration of high G value acceleration sensor [19,20], and there are also related application research in China [21]. At present, the traditional evaluation of the safety of gunwork products is to use Machet hammering method, but the overload acceleration of Machet hammering method can not reach the actual overload of pyrotechnics. Nanjing University of Science and Technology Zhang Xueshun et al. [22] have applied Hopkinson pressure bar technology to the dynamic target simulation test of gunwork products, which has solved the difficult problem of ultra-high G value environmental simulation of pyrotechnics. A similar method can be used to evaluate the safety and structural stability of fuze [23]. Due to the shortage of experimental methods, the research progress on shear initiation criteria of explosives is slow. Recently, an improved SHPB was designed by the United States Army Laboratory to carry out shear stamping experiments on explosive materials. The critical shear velocity and critical wave time of explosive initiation were determined by adjusting the shear speed and wave time by changing the bullet speed and length [24].

3. Development of Dynamic Mechanics of Girth Weld

In the field of pipeline research, the evaluation methods of residual strength are summarized as follows: (1) based on the semi-empirical formula obtained by hydraulic blasting test of a large number of defective pipe segments; (2) the analytical analysis method based on elastic-plastic mechanics and fracture mechanics theory; (3) the finite element numerical calculation method; and (4) based on the failure criterion of defective pipeline, combined with probability and reliability theory, the probabilistic integrity evaluation method of defective pipeline is established.

The evaluation method of residual strength of defective pipeline has been studied since the early 1970s in the world, and many evaluation standards and norms have been formed at present. For the evaluation of volume defects, based on the semi-empirical fracture mechanics relationship established by Kiefner and Maxey et al. [25,26] in the 1970s, the evaluation criteria and norms represented by ASME B31G [27] and CAN/CSA Z144-M86 [28] are formed. Since 1990s, in order to avoid the excessive conservatism of B31g method, a lot of research has been carried out on the evaluation method of local corrosion defects in the world, and new standards and methods have been promulgated, including chapter 5 of DNV RP F101 [29] and API RP 579 [30]. For the evaluation of planar defects, elastic-plastic fracture analysis methods are mainly used, including EPRI method [31], CEGB R6 [32] method, ASEMXI appendix C "Austenite Pipeline defect acceptance Criterion and Evaluation Code" [33] and IW-3650 Appendix C "Ferrite Pipeline defect acceptance Criterion and Evaluation Code" [34]. For the eighth chapter of geometric defect, API RP 579, the evaluation methods of pipe body non-circle, straight weld pout mouth and wrong edge are given. In chapter 6 of API RP 579, the evaluation method of point corrosion damage is given, but the evaluation process, especially the quantitative process of defects, is too complex to be operated and applied in engineering. In addition, only a rough guiding method is given for the evaluation of hydrogen bubbling. Although a lot of research has been carried out in the world since the end of 1980s, there is no systematic evaluation standard and standard for the evaluation method of mechanical damage defects.

In the aspect of dynamic impact of girth welds, the commonly used impact dynamics experimental methods are limited to the use of Charpy (CVN) impact test, drop hammer tear test (DWTT), and fracture toughness test (KIC,CTODJ integral) to qualitatively measure and characterize the ability of materials to resist fracture. The results are also used to assist in the study of the calculation formula derived under quasi-static conditions, but there is no systematic research method. At present, most of the research on the dynamic impact behavior of pipeline girth weld is aimed at a specific accident, and the dynamic impact process is roughly analyzed. Lu Guoyun et al. [35] in 2003, the impact failure of three-span continuous pressure pipeline was studied by using DH R-9401 impact loading tester, and the critical failure speed and corresponding failure mode under different working conditions were
obtained. Emin Bayraktar et al. [36] used impact tensile test (impact tensile test, in 2004. ITT) and Charpy impact strength test (V-notch) were used to study the effect of strength mismatch on fracture position of laser welding girth weld of offshore pipeline. Wang Hong et al. [37] deduced the formula for calculating the impact force of falling stone on pipeline by means of theoretical mechanics in 2009, and the results are in good agreement with the actual situation. Tan Xuegang et al. [38] calculated the impact of blasting collapse on underground pipeline by using engineering mechanics theory in 2012. Liu Shuo [39] combined with chemical composition analysis technology, scanning electron microscope (scanning electron microscopy, SEM) and scattering energy spectrum measurement technique (energy dispersive spectrometry, in 2014. EDS) the impact strength of three kinds of self-shielded tubular cored girth welds is estimated. Hang Zhang [40] studied the impact effect of internal testing tool (Pipeline inspection gauges, PIG) on pipe girth welds by finite element simulation in 2015.

4. Conclusion and Prospect
At present, the research on dynamic impact of pipeline girth weld at home and abroad is limited to obtaining the impact strength of weld by a certain experimental means, or using a certain theory to calculate the dynamic impact force, which has not yet formed a systematic research method from material to structure, from theory to experiment, and the mature theory and experimental technology in the field of dynamic impact mechanics have not been fully utilized. Because the pipeline girth weld is an uneven material, the propagation process of stress wave between girth weld and wood involves many complex reflection and transmission. It is difficult to accurately grasp the dynamic impact damage mechanism and evolution law of girth weld by single theoretical calculation or numerical simulation. Therefore, the applicant believes that the dynamic damage study of girth weld in the future needs dynamic mechanics of fusion material and dynamic mechanics of structure. The theoretical basis and experimental technology of impact dynamics and the structural dynamics simulation module of finite element simulation can be carried out in order to have a scientific and systematic understanding of the dynamic mechanical behaviour of girth weld and to provide a full and scientific theoretical basis for the engineering application of dynamic damage of girth weld.

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6. References
[1] Liu M, Wang Y, Horsley D. Significance of HAZ [heat affected zone] softening on strain concentration and crack driving force in pipeline girth welds. Offshore Mechanics and Arctic Engineering (OMAE 2005). Proceedings, 24th International Conference, Halkidiki, Greece, 12–17 June 2005.
[2] Bastola A, Wang J, Shitamoto H, et al. Investigation on the strain capacity of girth welds of X80 seamless pipes with defects. Eng Fract Mech, 2017: S0013794416306397.
[3] Hertelé S, O'Dowd N, Minnebruggen K V, et al. Fracture mechanics analysis of heterogeneous welds: Numerical case studies involving experimental heterogeneity patterns. Eng Fract Mech, 2015, 58:336-350.
[4] Hoh H J, Pang J H L, Tsang K S. Stress intensity factors for fatigue analysis of weld toe cracks in a girth-welded pipe. Int J Fatigue, 2016: S0142112316000402.
[5] Paredes M, Ruggieri C. Engineering approach for circumferential flaws in girth weld pipes subjected to bending load. Int J Pres Ves Pip, 2015, 125:49-65.
[6] Fu A Q, Kuang X R, Han Y, et al. Failure analysis of girth weld cracking of mechanically lined pipe used in gas field gathering system. Eng Fail Anal, 2016, 68:64-75.
[7] Lee C H, Chang K H. Failure pressure of a pressurized girth-welded super duplex stainless steel pipe in reverse osmosis desalination plants. Energy, 2013, 61(Complete):565-574.
[8] Chang K H, Lee C H, Park K T, et al. Analysis of residual stress in stainless steel pipe weld subject to mechanical axial tension loading. Int J Steel Struct, 2010, 10(4):411-418.
[9] Pan Jiahua. Fracture mechanics analysis of oil and gas pipeline. *Petroleum Industry Press*, 1989. (in Chinese)

[10] Starostin V. Pipeline disaster in the USSR. *Pipes Pipelines Int*, 1990, 35(2): 7-8.

[11] Li H, Zhao X, Ji L. Failure analysis and integrity management of oil and gas pipelines. *Oil and gas storage and transportation*, 2005, 24 (S1): 1 - 7. (in Chinese)

[12] Dannemann K A, Chalivendra V B, Song B. Dynamic behavior of materials. *Exp Mech*, 2012, 52(2): 117-118.

[13] Chen W W, Song, B. *Split Hopkinson (Kolsky) bar: design, testing, and applications*. US: Springer, 2011. C. Flaw distribut

[14] Greene, H, ions and the variation of glass strength with dimensions of the sample. *J Am Ceram Soc*, 2010, 39(2): 66-72.

[15] Song B, Chen W W, Jiang X. *Split Hopkinson pressure bar experiments on polymeric foams*. *Int J Vehicle Des*, 2005, 37(2-3): 185-198.

[16] Klepacko j, Brara a. An experimental method for dynamic tensile testing of concrete by spalling. *Int J Impact Eng*, 2001, 25(4): 387-409.

[17] Gálvez F, Rodríguez Pérez J, Sánchez V. The spalling of long bars as a reliable method of measuring the dynamic tensile strength of ceramics. *Int J Impact Eng*, 2002, 27(2): 161-177.

[18] Hu S, Zhang L, Wu N. Experimental study on spallation strength of concrete materials. *Engineering Mechanics*, 2004, 21 (4): 128 -132.(in Chinese)

[19] Robert D S. Testing techniques involved with the development of high shock acceleration sensors. *In Range Commanders Council Twelfth Transducer Workshop*, 1983.

[20] Togami T C, Baker W E, Forrestal M J. A split Hopkinson bar technique to evaluate the performance of accelerometers. *Int J Vehicle Des*, 2005, 37(2-3): 185-198.

[21] Li Y, Guo W. Research on Calibration system of High g acceleration Sensor. *Explosion and shock*, 1997,17 (1): 90-96.(in Chinese)

[22] Zhang X, Shen R. Research on Simulation Technology of dynamic targeting of initiating products. *Gunwork*, 2003, 4 (1-4).(in Chinese)

[23] Zhang M, Wu Z. Test technology of chamber explosion point. *Journal of Detection and Control*, 1994,21 (2): 9-15.(in Chinese)

[24] Brian K, Oliver Be, Robert L, et al. Shear deformation and shear initiation of explosives and propellants. *Symposium of 12th Detonation*. 2003.

[25] Kiefner J F, Maxey W A, Eiber R J, et al. Failure stress levels of flaws in pressurized cylinders. *Astm Special Technical Publication*, 1973. 536,461-481.

[26] Maxey W A, Kiefner J F, Eiber R J, et al. Philadelphia: ASTM, 1972.

[27] ASEM: Manual for Determining the Remaining Strength of Corroded Pipelines. 1991.

[28] CAN /CSA Z184-M86: Gas pipeline systems. 1986.

[29] DN V RP F101: Corroded Pipelines. 1999.

[30] API 579-2000: Recommended practice for fitness for service. 2000.

[31] Kumar V, German M D, Shih C F. Palo Alto: EPRI, 1981.

[32] Milne I, Ainsworth R A, Dowling A R, et al. Assessment of the integrity of structures containing defects. *International Journal of Pressure Vessels and Piping*, 1988, 32(1): 3-104.

[33] ASEM XIIWB-3640 and Appendix H: Flaw evaluation procedures and acceptance criteria for austenitic piping. 1986.

[34] ASEM XIIWB-3650 and Appendix C: Flaw evaluation procedures and acceptance criteria for ferritic piping [D]. 1986.

[35] Road N, Lei J, Wu Y, et al. Experimental study on lateral impact failure of multi-span thin-wall pressure pipeline. *Explosion and shock*, 2003, 23 (5): 454-459.(in Chinese)

[36] Bayraktar E, Hugel D, Jansen J P, et al. Evaluation of pipeline laser girth weld properties by Charpy (V) toughness and impact tensile tests. *J Mater Process Tech*, 2004, 147(2): 155-162.

[37] Wang H, Yu Z. Quantitative analysis of impact effect of falling stone on buried pipeline. *Petroleum Engineering Construction*, 2009, 35 (6): 5-8.(in Chinese)

[38] Tan X, May D, Tian Y, et al. Discussion on impact effect of blasting collapse on underground pipeline. *Blasting*, 2012,29 (1): 23-26.(in Chinese)
[39] Liu S. Investigation of the impact toughness of self-shielded flux-cored wire girth welds for X80 pipelines. *Baosteel Technical Research*, 2014, 8(4): 53-60.

[40] Zhang H, Zhang S, Liu S, et al. Measurement and analysis of friction and dynamic characteristics of PIG’s sealing disc passing through girth weld in oil and gas pipeline. *Measurement*, 2015, 64,112-122.