Research and Method for In-line Inspection Technology of Girth Weld in Long-Distance Oil and Gas Pipeline

Pengchao Chen, Rui Li*, Kuan Fu, Xiaoming Zhao
PipeChina North Pipeline Company Langfang, China
kjrirui@petrochina.com.cn

Abstract. With the increasing demand for energy, long-distance oil and gas pipeline has become the main mode of transportation of oil and gas resources. High pressure, inflammable and explosive medium, complex and changeable route environment and other factors make the safe transportation of pipeline concerned. The girth welds of oil and gas pipeline have always been the weak part of the pipeline due to the technical level during the construction, on-site welding practices and operation environment, and the girth weld cracking is one of the main failure forms of oil and gas pipeline. It is an effective way to ensure the safety of pipeline to adopt various advanced and targeted inspection to identify pipeline defects, judge the types of defects, and then carry out safety evaluation and maintenance. This paper analyzes the main failure factors of girth weld of oil and gas pipeline, and systematically summarizes the content and methods of various in-line inspection on girth weld in view of these failure factors, so as to provide reference for the development and application of in-line inspection technology on girth weld of oil and gas pipeline.

1. Introduction

Oil and gas pipeline is a main artery of national economy[1-2], and the safety of pipeline is closely related to people's life and social and economic development. Although pipeline transportation is the safest and most reliable mode of oil and gas transportation, leakage occurs every year due to welding, corrosion, local damage and other reasons, resulting in serious economic losses and human casualties. Among them, due to the technical level during the construction, on-site welding practices and operation environment and other factors, the girth welds of oil and gas pipeline have always been the weak part of the pipeline, and the girth weld cracking is one of the main failure forms of oil and gas pipeline[3-4].

In recent years, with the continuous increase of pipeline mileage, many girth weld failure accidents have occurred at home and abroad. According to the failure accidents from 2010 to 2012 published by the American Association for Pipeline and Hazardous Materials Safety, there were 8 accidents caused by girth weld cracking of gas pipeline alone, among which 3 accidents occurred in the pipelines newly put into operation[5]. In China, girth weld cracking accidents caused by incomplete root welding, large external load and misalignment also occurred in the Second West-East Gas Pipeline, Zhongwei-Guizhou Pipeline and China-Myanmar Pipeline in recent years[6-8].

According to the various accidents occurred in recent years, the following characteristics are summarized: firstly, the accidents occurred most frequently in newly built and put into operation gas transmission pipeline of large diameter and high strength steel, especially X70, X80; secondly, the fault welded joints are mostly those in wall thickness transitioning or repaired joints or connector joints, showing a brittle fracture on the field, high probability of explosion, difficult to repair and serious failure consequences; thirdly, it is mostly related to the quality control during the construction, showing the
existence of defects exceeding the standard limit, non-standard alignment, substandard or uneven welding joint toughness, and excessive additional stress. The girth weld cracking of oil and gas pipeline is characterized by long cracking length and large leakage[9]. Once the girth weld failure occurs, it will cause serious threat to the surrounding personnel and environment along the pipeline and result in great economic loss.

Therefore, pipeline operators at home and abroad have been building integrity management idea and system of pipeline. In addition to establishing strict technology and management requirements, and conducting appearance, X-ray and ultrasonic inspection for girth welds during pipeline construction, various advanced inspection technologies are also used to detect, identify and quantify defects, stress and other risks during pipeline operation, so as to carry out safety evaluation on the failure risks of pipeline girth welds and corresponding repair & maintenance to ensure the intrinsic safety of oil and gas pipelines. In this paper, the main factors of girth weld failure of oil and gas pipeline are analyzed, and the content and various in-line inspection methods of girth weld are summarized systematically in view of these failure factors, so as to provide reference for the development, research and application of girth weld in-line inspection technology of oil and gas pipelines.

2. Analysis on Failure Factors of Pipeline Girth Weld

According to statistics, there are 10 pipeline girth weld failure accidents publicly reported in North America in recent 2-3 years, mainly for in-service pipelines, and a few leakages occurred in the hydraulic test process. The types of steel pipes in the failure accidents are all ERW pipe and SSAW pipe, and their steel grades are from X52 to X80. Among them, there are 2 failure accidents of X52 girth weld, 1 failure accident of X70 and X80 butt girth weld, and the rest are X70 girth weld failure accidents. In 2008 and 2009, the United States concentrated on the construction of a number of high-grade steel pipelines (about 6400 Km per year). During the pipeline hydraulic testing, the quality problems of pipes and girth welds were found, including pipe bulging, deformation, cracking and girth weld leakage. Subsequently, girth weld cracking accidents also occurred in the pipelines in service. To this end, the U.S. government required the pipeline companies to conduct a comprehensive inspection on pipelines with DN508 and above in diameter and X70 and above in material grade, which are built in 2008 and 2009. On March 18, 2010, the Pipeline & Hazardous Materials Safety Administration (PHMSA) under the U.S. Department of Transportation issued PHMSA-2010-0078 "Pipeline Safety: Girth Weld Quality Issues Due to Improper Transitioning, Misalignment, and Welding Practices of Large Diameter Line Pipe"[10]. Accident analysis shows that these failure events are caused by improper welding of girth weld in wall thickness transitioning, misalignment, improper internal welding of pipeline, improper pipe support and accessories, and the conditions of most pipe ends to be welded do not meet the design and construction requirements (i.e., the groove is treated inadequately). Most of the failed welds have defects, with the strength, chemical composition and weld toughness of the steel pipe do not meet the requirements of relevant standards. Pipeline girth weld failure is mainly caused by the following three main reasons:

2.1. the Overall Performance of the Material does not Meet the Requirements

1) Weld toughness index is not up to standard and uneven: improper control of welding parameters, too fast cooling rate, uneven weld structure, insufficient welding layers, larger heat input of self-shielded semi-automatic welding than that of solid wire automatic welding, repair and other reasons.

2) Heat affected zone softening: the alloy composition of steel, increased fine grain size, too large welding heat input.

3) Low matching of weld strength: the rolling process and pipe making process of different manufacturers have great influence on the strength distribution of steel pipe, so it is difficult to ensure equal strength matching in welding process design; the weld metal strength is greatly affected by cooling rate, multiple thermal cycles, repair and other factors.
2.2. **Weld Defects**

The defects of field-produced girth welds of oil and gas pipelines can be divided into the planar defects, the volumetric defects and the defects of irregular shape[11].

1) The volumetric defects (porosity, slag inclusion, concave, unfilled weld, etc.) are relatively less harmful, and only the plastic failure mode is considered.

2) The planar defects (incomplete fusion, incomplete penetration, cracks, etc. as shown in Fig. 1) are relatively more harmful. The crack initiation points are mostly located at the root weld defects, and the planar defects at the root weld are the main cause of cracking. At present, in the oil and gas pipeline girth weld cracking accidents at home and abroad, most of the defects are caused by cracks, incomplete penetration, incomplete fusion and sharp undercut. The high stress concentration of these planar defects greatly weakens the bearing capacity of the pipeline, which is the focus of non-destructive inspection of girth weld defects of oil and gas pipelines.

3) The defects of irregular shape include irregular weld contour, misalignment, etc.. Misalignment is the dislocation of the edges of the two pipes during welding (Fig. 1), which reduces the effective wall thickness and may cause additional bending stress. Due to field construction and other factors, it is prone to forming irregular shape for girth weld when carrying out bottom welding of the pipeline.

![Figure 1 Girth weld crack defect.](image)

2.3. **Off-design Load (Additional Stress) on Pipeline**

Stress refers to the load borne on the unit area of the material, and the stress on long-distance oil and gas pipeline can be divided into membrane stress and bending stress according to their nature[12-13].

1) The membrane (axial) stress refers to the stress component uniformly distributed along the section thickness, which is equal to the average stress along thickness of the section considered. It is generally understood as axial stress, which mainly includes internal pressure or uniform external pressure; thermal effect (thermal expansion or thermal contraction) caused by the too large difference between the temperature when the pipeline is lowered into the trench and buried and the temperature during operation; the assembly stress caused by removal of line-up clamp after root welding, the lifting and forced...
alignment of pipe sections, pipe bending in the process of lowering into trench and non-standard construction; axial deformation component in the process of pipeline bending deformation caused by geological change or external force; axial stress component generated by skew joint, wall thickness transitioning, misalignment and local deformations at or near the weld, such as depression, fold and ellipse deformations.

2) Bending stress refers to the total stress after removing the uniformly varying membrane stress, and its variation along the thickness can be linear or nonlinear. It mainly includes the stress generated by the pipe dead weight (for suspended pipe); the bending deformation component caused by geological change or external forces, as shown in Fig. 2, which is the comparison before and after repair of bending strain caused by longitudinal displacement of pipeline; the bending component of assembly stress, the bending component of local stress (peak stress), etc.

Generally speaking, the stress caused by the bending deformation of the pipeline due to the geological disasters such as debris flow and landslide and the influence of accumulated heavy objects is usually not a simple bending, but the superposition of pipeline axial deformation and bending deformation.

![Figure 2](image)

Figure 2 Comparison before and after repair of bending strain caused by longitudinal displacement of pipeline.

At present, the long-distance oil and gas pipelines are characterized by higher strength and toughness of pipeline steel, changing wall thickness and larger pipe diameter, and then different methods, materials and processes for welding are produced. The microstructure and mechanical properties of the welded joint of pipeline undergoing special thermal process are extremely uneven, which inevitably leads to various defects. Moreover, the long-distance pipeline route area is complex and changeable, and it often encounters the areas prone to geological disasters, which also makes the pipeline face the risk of additional stress. The pipeline welding area is usually sensitive to crack initiation and propagation in the structure. When defects, materials, loads and other factors act at the same time or some of them act at the same time, it is easy to cause weld failure. Therefore, in order to solve the problem of girth weld failure, inspection and evaluation should be carried out from the following three aspects:

1) The key for the material is to ensure the toughness index and uniformity of the whole welding joint (avoiding the problems such as the dispersed and substandard toughness, the softened heat-affected zone, and the poorly matching in weld strength). Once the weld is formed, it is difficult to detect online during the operation period.

2) Defects are represented by defect type and defect size. Volumetric defects only affect strength, while for planar (crack) defects, additional consideration should be given to fracture mechanics, which are very different from each other. For the planar defects, the root welding part is the most dangerous and needs the most attention, which is prone to incomplete penetration, incomplete fusion, cracks, etc. Therefore, the in-line inspection of in-service pipeline should focus on the inspection and research of planar defects at root welding parts.

3) The load problem is more complicated. In addition to the conventional internal pressure, the main consideration should be given to the construction assembly stress and the external displacement stress, which is manifested as axial stress and bending stress. Under the action of these additional stresses, the minor planar defects that are normally acceptable may lead to cracking, expansion until failure.
Therefore, the in-service inspection of the stress (axial stress and bending stress) on the pipeline weld is also a key point to tackle in girth weld inspection technology.

After nearly 30 years of development, the domestic and foreign pipeline inspection service providers have successively developed triaxial high-definition magnetic flux leakage (MFL) in-line detector[14-18] and technologies of liquid ultrasonic inspection[19-21], electromagnetic acoustic transducer (EMAT)[22-25] for crack inspection, etc[26-27]. which are applied to the inspection of corrosion, stress corrosion crack and other defects of oil and gas pipeline. However, the irregular shape of girth weld, narrow width of girth weld, sensor hopping, large lift-off, etc. restrict the inspection of girth welds defects by in-line inspection technology. In addition, the in-line inspection of pipeline stress and material has been one of the international difficulties. With the continuous development of in-line inspection technology, domestic and foreign pipeline inspection companies are working closely with pipeline operators to improve the current oil and gas pipeline in-line inspection technology and equipment, and carry out special research and application of in-line inspection technology of pipeline girth welds.

3. In-line Inspection Technology For Girth Weld Defects of Oil and Gas Pipeline

3.1. Triaxial High-definition MFL in-line Detector

MFL inspection is a general in-line inspection technology, which is mainly used to detect metal loss and other volumetric defects. The technical principle of MFL in-line inspection is to judge the defect degree of the workpiece by measuring the leakage flux on the surface of the magnetized ferromagnetic material [28-32]. After ferromagnetic material is magnetized by an external magnetic field, if the texture of the ferromagnetic material is continuous and uniform, the magnetic field lines in the material will be constrained inside the material, and almost no magnetic field lines will come out of the surface of the material, as shown in Fig. 3 (a); however, when there are defects on the surface or inside of ferromagnetic material, the magnetic field lines will change their path due to the small permeability and large reluctance at the defect position, and pass through the texture with small reluctance in preference; when the magnetic induction intensity inside the material is relatively large or the defect size is large, it is difficult for the material near the defect to accept larger magnetic flux, and part of the magnetic flux will overflow the workpiece from the defect, cross over the workpiece defect, and then enter the workpiece, forming a leakage magnetic field outside the workpiece, as shown in Fig. 3 (b). The magnetic sensor is used to collect the leakage magnetic field and convert it into electrical signal. The defect can be captured by calculating the electrical signal.

![Figure 3 Principles of magnetic flux leakage inspection.](image)

![Figure 4 Distribution of defect magnetic field.](image)
The early MFL inspection technology is mainly used to detect the internal and external corrosion defects of pipelines. It only records the axial component of the leakage magnetic field, and is not sensitive to the axial groove and crack defects parallel to the direction of the leakage magnetic field. As a result, the inspection rate and identification rate of the ordinary MFL detector for the axial groove and crack are low [33-34]. With the improvement of defect inspection rate and quantization accuracy, triaxial high-definition MFL inspection technology is introduced[35]. Based on the original single sensor, two groups of orthogonal Hall sensors are added in the triaxial high-definition MFL in-line detector to detect the size of the magnetic flux leakage at the defect of the pipe wall, and measure the axial, circumferential and radial magnetic flux leakage value respectively, which is used to determine the three-dimensional magnetic flux leakage vector and more clearly describe the defect[36-37]. The axial signal of defect leakage magnetic field shows an unipolar wave, and the amplitude can reflect the defect depth; the radial signal is a bipolar sinusoidal wave with the same peak and trough values, the amplitude is related to the defect depth, and the distance between the peak and trough reflects the defect length; the circumferential signal shows both positive and negative polarity in the radial and circumferential directions, which directly reflects the length and width of the defect. Comprehensive analysis of the three axial components of leakage magnetic field can improve the identification rate and dimensional quantization accuracy of defects[38-39].

![Figure 5 Schematic diagram of triaxial high-definition MFL in-line detector.](image)

At present, the dimensional accuracy of triaxial high-definition MFL inspection is ±10%, and the confidence level is more than 90%, which can meet the requirements of conventional volumetric inspection for oil and gas pipelines. However, the principle of MFL inspection determines that it can only detect partial volumetric defects in girth welds at present, such as incomplete welding, over-grinding, incomplete fusion and incomplete penetration with large opening, and large-size undercut, but cannot detect the defects such as incomplete fusion and incomplete penetration with small opening, crack and small-size undercut[40]. Moreover, for the defects that can be detected, the type of defects cannot be distinguished, and the accuracy of dimensional quantification is not high. The quantitative depth of some in-line inspection results is given as severe, moderate and mild, which is difficult to evaluate the applicability. Kinder Morgan, TransCanada and other pipeline operators have cooperated with inspection service providers to carry out MFL inspection research on girth weld defects, and CNPC Pipeline Company has also carried out relevant experimental research, but the actual inspection effect has not reached the expectation.

In order to further detect minor defects (such as cracks, pinholes, etc.), foreign companies for in-line inspection such as Rosen have developed ultra-high-definition triaxial MFL in-line detector[41]. It uses probes in double rings and double rows to improve the circumferential resolution through a certain slight dislocation, making the arrangement density of axial probes up to 1.6 mm for circumferential, radial and axial measurements, as shown in Figure 6; the axial inspection accuracy is further improved, and the axial inspection resolution is up to 1 mm; the distance from Hall sensor to pipe body is also greatly reduced; and the double-layer design of Hall sensors enhances the accuracy of data and corrosion growth rate analysis, as shown in Figure 7, which shows the comparison between HD and UHD MFL signals.
But at present, due to the high inspection cost and the few specifications of this kind of detector, it has not been widely used.

![Figure 6](image1.png)

**Figure 6** Comparison of HD and UHD MFL probe arrangement.

![Figure 7](image2.png)

**Figure 7** Comparison of HD and UHD MFL signals.

Although MFL in-line inspection technology has some limitations on girth weld crack defects, it can detect gas pipeline girth weld defects and many other types of defects without coupling agent[42]. Especially the introduction of UHD triaxial MFL in-line detector can greatly improve the inspection rate of girth weld cracks and other defects. Therefore, for the inspection of girth weld defects in oil and gas pipelines, the UHD triaxial MFL detector should be extensively promoted, experimented and applied in the field, and the data analysis model should be improved and the inspection accuracy improved.

3.2. Crack Ultrasonic In-line Detector

Crack ultrasonic in-line detector is a kind of ultrasonic measurement equipment based on pulse echo time technology. By adjusting the propagation angle of the ultrasonic pulse entering the pipe wall through the liquid coupling medium (oil, water, etc.), the shear wave can be generated in the pipe wall, and the position and size of the internal defects can be detected by the ultrasonic echo. Ultrasonic in-line inspection technology can be divided into two types: one is to emit ultrasonic pulse perpendicular to the pipe wall, and the ultrasonic pulse will be reflected both on the inner and outer surfaces of the pipe wall. The lift-off value from the sensor to the inner wall and the wall thickness of the pipe can be calculated according to the time when the echo of the two pulses received by sensor, which can be used to identify and quantify the volumetric defects; the other is to emit a 45° shear wave to the pipe wall, the shear wave will be reflected at the defect, which is used to detect stress corrosion crack (SCC) and circumferential crack defects. The 45-degree shear wave is generally used to detect cracks in oil and gas pipelines[43-45].

The development process of pipeline ultrasonic in-line inspection technology can be summarized into three stages[46]. In the first stage, the ultrasonic in-line detector can only complete the inspection of defect with large area, and the detector has a large volume and poor passing ability; in the second stage, the overall structure of the ultrasonic in-line detector is optimized, and the passing ability is improved. With the progress of the sensitivity and storage technology of inspection components, the accuracy of the sensor is improved, and the ultrasonic in-line inspection level is greatly improved; in the third stage, by using phased array technology, ultrasonic in-line detector has ultra-high resolution and
inspection accuracy. At the same time, with the development of computer image processing technology, there are more options for the realization of inspection results.

The ultrasonic phased array detector adopts the arrangement of ultrasonic probes in groups. These probes are densely arranged, and several adjacent probes form a group. The probes in a group emit ultrasonic pulse signals to different directions and angles according to a certain time sequence, which has higher resolution and inspection accuracy. It can not only detect metal corrosion and crack defects, but also stress corrosion cracking, fatigue cracking and welding cracking defects[47-50]. PII company has developed ultrasonic phased array detector Uhrascan Duo, which is an in-line inspection tool that can simultaneously detect cracks and metal loss. It uses the phased array technology with higher resolution developed by GE Healthcare for the diagnosis of brain, spine and soft tissue, which can achieve higher data resolution and accuracy during in-line inspection. Duo employs adaptive orthogonal and angular ultrasonic beams at the same time to optimize the probability of inspection and identification for various cracks and metal loss defects. It can detect a variety of crack defects, such as weld cracking, hydrogen induced cracking, fatigue cracking, shrinkage cracking, SCC and incomplete fusion.

At present, crack ultrasonic inspection technology is relatively mature in the inspection of pipe axial cracks or straight weld cracks, which can detect tiny cracks[51-52], including stress corrosion cracks, fatigue cracks[53-54], etc. However, this technology has a high requirement on the surface cleanliness of the pipeline, so it cannot be applied to the oil pipeline with serious wax deposition on the pipe wall or more oil impurities. In addition, because ultrasonic needs liquid as coupling agent, it is not suitable for in-line inspection of gas pipeline[55-56].

![Figure 8 Schematic diagram of crack ultrasonic in-line inspection.](image-url)

Due to the uncertainty of in-line inspection market expectation for in-service pipeline girth weld, the complexity of inspection, and the fact that X80 steel pipeline is not widely used in the world, the attention to girth welds is far less than that paid by pipeline companies in China. Therefore, most of the crack ultrasonic inspection equipment in the industry is used for axial crack defects, and the development of girth weld in-line inspection technology is relatively slow.

CNPC Pipeline Company cooperated with GE PII to study the applicability of crack ultrasonic inspection on girth weld, and conducted field test on Mohe-Daqing Pipeline[57]. The traction test showed that the circumferential ultrasonic in-line inspection technology can effectively detect the relatively regular man-made cracks of girth weld. However, the actual pipeline application is affected by the irregular formation of girth weld, uneven residual height, row welding, repair, etc., as well as the lack of a large number of real defect samples to support the data analysis model. As a result, this technology still has large errors in the classification, quantification and internal and external differentiation of defects, and it is still far from the industrial application.
3.3. Electromagnetic Acoustic Transducer (EMAT) In-line Detector

In traditional ultrasonic inspection, the coupling agent needs to be added between the probe chip and the workpiece to be detected, and the required surface smoothness of the workpiece is high, so it is not suitable for long-distance oil and gas pipeline inspection [58-59]. The EMAT in-line inspection technology is mainly developed for the crack inspection of gas pipelines, which solves the problem of traditional ultrasonic inspection technology requiring coupling agent. It has a good effect in detecting axial crack and stress corrosion crack (SCC) [60-61], and has a good application prospect in the field of online inspection of oil and gas pipeline [62].

The EMAT detector forms a magnetic field in the pipe wall through a permanent magnet or an electromagnet. The eddy current is generated inside the pipe wall by using an AC coil which is at 90° to the magnetic field. The ultrasonic wave propagating along the pipe wall is generated by applying a force perpendicular to the pipe wall on the eddy current [63-64]. EMAT can also be used in gas pipeline because it does not require liquid coupling agent to transmit the ultrasonic wave to the pipe wall like traditional ultrasound does. When there is no defect in the pipe, the propagation of electromagnetic ultrasonic wave along the pipe wall will only be attenuated; when there is defect in the pipe, it will interfere with the propagation of electromagnetic ultrasonic wave and generate reflection signal, from which the type and size of defect can be calculated. The advantages of EMAT in-line inspection technology are that it does not need liquid coupling agent, can operate in liquid and natural gas pipelines, has the characteristics of high resolution and high precision, and has strong inspection ability for defects such as anti-corrosion coating peeling, stress corrosion crack, pipe seat crack, fatigue crack and crack near weld [65-66].

The pipeline EMAT inspection system consists of three parts: excitation, propagation and reception, which respectively are the exciter used to generate the bias magnetic field, the specimen to be detected and the coil connected with high frequency alternating current [67-68]. The exciter can be a permanent magnet or an electromagnet. The specimen is placed in the bias magnetic field as the electromagnetic ultrasonic wave propagation carrier. After the coil placed on the pipe wall is connected with the high frequency alternating current, the alternating electromagnetic field will be generated around the specimen and the eddy current will be induced in the specimen. Under the action of bias magnetic field, the alternating force or deformation will be produced on the surface of the specimen, and vibration is generated in turn and propagated in the specimen to form ultrasonic wave. When receiving the ultrasonic wave, the vibration of micro particles in the specimen causes the disturbance of bias magnetic field, because of the Faraday effect, the coil cuts the magnetic field lines and generates voltage, so as to realize ultrasonic measurement. In ferromagnetic materials, magnetostrictive effect is the dominant factor affecting EMAT efficiency. The propagation of ultrasonic wave is carried out by using the inner and outer surfaces of the pipe wall as the “waveguide”, when the pipe wall is uniform, the wave will only
attenuate along the pipe wall; When there are abnormalities on the pipe wall, such as stress corrosion crack (SCC), corrosion coating peeling, etc., they will interfere with the guided wave, and produce echo signal, which can be measured to accurately infer the characteristics and conditions of the pipe wall cracks and coating.

Since the type and structure of the sensor determine the form of the generated ultrasonic wave and the characteristic of the ultrasonic wave propagating in the pipe wall, by modifying the structure of EMAT sensor, the detector can generate waves in different directions during in-line inspection to detect the pipe body, such as transverse wave. Since EMAT does not require coupling, it is suitable for inspection of gas and liquid pipeline. In addition, EMAT also has the ability to detect the coating type of pipeline and the coating peeling condition. At present, ROSEN’s EMAT technology is relatively mature, and it has a performance of more than 50,000 kilometers accumulated in the world, and has verified at least 4,254 crack defects, covering 12”- 48” pipelines; PII company of the United States has developed EmatScan CD in-line detector for both liquid and gas pipelines, and its inspection rate of long and narrow cracks with a length greater than 50 mm and a depth greater than 2 mm is more than 90%. It can detect minor SCC and coating peeling, as well as other forms of longitudinal cracking, including fatigue cracking, weld toe cracking, structure cracking, long cracking and incomplete fusion cracking around joints. It can also accurately detect depressions and cracks caused by mechanical damage.

However, the reliability of EMAT inspection for girth weld crack defects has not been reported publicly. The applicability of EMAT inspection technology for girth weld defects needs further research and experimental verification.

3.4. Electromagnetic Eddy Current Inspection Technology

Pipeline electromagnetic eddy current inspection is based on the principle of electromagnetic induction, which is suitable for conductive materials. When a certain frequency of alternating excitation is applied to the surface of the conductor, it will produce alternating eddy current in the conductor, which in turn produces a constant secondary magnetic field within a certain range. When the conductor is discontinuous, the alternating eddy current is blocked, so that the secondary magnetic field generated by the eddy current changes, that is, "scarce", resulting in a sudden change of the secondary magnetic field. Through the measurement coil set at a certain distance from the excitation coil, it can effectively receive the magnetic field changes that pass through the pipe wall and return to the pipe, and detect the defects in the inner wall of the pipeline[69-72]. Eddy current inspection requires alternating excitation device, and the output signal is of high frequency. The probe should not be made of metal material, otherwise it will shield the eddy current effect caused by AC excitation.

![Schematic diagram of electromagnetic eddy current inspection.](image)

JENTEK Sensor’s electromagnetic eddy current technology based on winding magnetometer array has been proved to be able to identify the axial crack of oil and gas pipeline and determine the crack size[73]. Nanjing University of Aeronautics and Astronautics and Shanghai Research Institute of Materials have made great breakthroughs in mechanism research and equipment development of far-
field eddy current inspection technology. Since then, a series of eddy current detectors developed by Edson (Xiamen) Electronics Co., Ltd. and others have also achieved good results.

At present, this inspection method is generally used for non-destructive inspection, which can effectively detect the surface cracks of workpiece, mold, etc. The special sensor for in-pipeline inspection has not been developed.

3.5. Alternating Current Field Measurement (ACFM) Inspection Technology

The excitation coil with alternating current will generate alternating magnetic field in the surrounding space. When the coil is close to the metal surface to be detected, the alternating magnetic field will generate induced current on the surface of the metal workpiece. Due to the skin effect, the induced current will gather on the surface of the workpiece, so as to generate uniform alternating current on the surface of the workpiece. The defects, cracks and fatigue damage in the material will change the distribution of the induced current around it, thus changing the distribution of the induced magnetic field on its surface. The crack inspection can be realized by detecting the magnetic field disturbance caused by the crack[74-77].

![Figure 12 Schematic diagram of ACFM.](image)

In practical application, the ACFM inspection technology is mainly used to determine whether there are cracks on the surface of metal workpiece by detecting the intensity change of the induced magnetic field. If the induced magnetic field is divided into three components BX, BY and BZ for analysis, BX is parallel to the crack propagation direction, BY is perpendicular to the crack propagation direction, and BZ is perpendicular to the crack propagation direction and perpendicular to the workpiece surface. When there is no crack on the metal surface, the magnetic field intensity BX does not change, and the values of BY and BZ should be zero. When there is a crack on the metal surface, the induced current field on the metal surface far away from the crack is uniform, and near the crack, the induced current lines will deflect along both ends of the crack, so that the induced current density at the center of the crack decreases and that at both ends increases[78-80]. The test results show that the change of the induced magnetic field intensity BY perpendicular to the crack propagation direction is very small and can be ignored. Therefore, BX and BY, which are perpendicular to each other, are the key parameters to determine whether there is a crack and to quantify the crack size. Generally, the butterfly curve formed by BX and BY components is used to determine the existence of cracks.
At present, this technology is mainly used for non-destructive inspection of submarine pipelines, and has been applied for many years. It has the following characteristics: sensitive to open crack of weld, low requirement for surface cleanliness, no coupling required, and a certain lift-off value allowed. This technology has not been developed into a special sensor for application in in-pipeline inspection.

3.6. Comparison of Girth Weld Defect Inspection Technology
The comparison of various current girth weld in-line inspection technologies is shown in Figure 14.

![Figure 14 Example of a figure caption.](image)

| Defect type                | MFL Inspection | Ultrasonic Crack Inspection | EMAT | Geometric Inspection | Electromagnetic Eddy Current | Alternating Electromagnetic Field |
|----------------------------|----------------|-----------------------------|------|----------------------|-------------------------------|----------------------------------|
| Well thickness transitioning| ✔              |                             | ✔    |                      |                               |                                  |
| Skew joint                 | ×              |                             | ×    |                      |                               |                                  |
| Misalignment               | ✔              |                             | ×    |                      |                               |                                  |
| Incomplete fusion          | ✔              |                             | ×    |                      |                               |                                  |
| Incomplete penetration     | ✔              |                             | ×    |                      |                               |                                  |
| Undercut                   | ×              |                             |      |                      |                               |                                  |
| Cracking                   | ×              |                             |      |                      |                               |                                  |
| Slag inclusion             | ✔              |                             |      |                      |                               |                                  |
| Porosity                   | ✔              |                             |      |                      |                               |                                  |

- Not applicable
- ✔ - applicable
- ✔ * - Applicable for defects with large opening on surface
- ✔ ** - Applicable for continuous development into volumetric defects
- ? - It has been confirmed to be applicable in the straight weld, and the application in girth weld inspection

4. In-line Inspection Technology for Girth Weld Stress of Oil and Gas Pipeline
In addition to the internal pressure, the additional load at the weld is the main factor affecting the crack initiation of conventional acceptable defects[81]. The additional load is usually caused by construction assembly stress and the bending deformation due to external displacement. The long-distance oil and gas pipelines generally have long distance and complex route, and they often pass through geologically unstable areas tending to occurrence of soil freezing, earthquake or flood. There may be various forms of bending deformation in the process of transportation, construction and later operation, such as pipeline bending caused by soil settlement: the pipeline will gradually enter a stable state under the effect of soil settlement within 1-2 years after the completion of laying[82-83]. During this period, the pipe body is prone to uneven stress and bending deformation under the influence of soil pressure and rock constraints; pipeline bending caused by sudden geological disasters: flood scour, debris flow,
earthquake and other sudden geological disasters will cause severe soil changes, impose great external load on buried pipeline, resulting in pipeline bending deformation and stress concentration; pipeline bending caused by periodic soil changes: the long-distance pipeline passing through seasonal swamp and cold area with freeze-thaw cycle will move periodically due to the continuous change of soil stress, resulting in bending deformation.

The additional loads on the pipeline are mainly bending stress and axial stress. The problem of bending stress measurement and evaluation can be well solved by pipeline centerline inspection with IMU[84-85]. The measurement of axial stress is still in the research stage, and the research focus is to test the feasibility of measuring axial stress by inspection of magnetoresistance[86-88] and weak magnetic and strong magnetic coupling[89], etc. under magnetostrictive effect and remanent magnetism.

4.1. In-line Inspection of Bending Stress (Strain)
In recent years, more and more pipeline operators tend to use high-precision inertial measurement unit (IMU) to identify and locate pipeline bending deformation and calculate bending stress (strain). The pipeline in-line inspection technology of IMU is to measure the three-dimensional relative position coordinates of the pipeline by IMU carried by the in-line detector, and uses high-precision reference point GPS coordinates on the ground to correct them, so as to accurately depict the three-dimensional trend of the pipeline centerline[90-92]. The core components of IMU are three-dimensional orthogonal gyroscope and accelerometer. When the detector is running in the pipeline, the current position coordinates are recorded. The gyroscope is used to measure the rotation angular velocity of the detector in three directions, and the accelerometer is used to measure the acceleration of the detector in the running direction. Through coordinate transformation and data processing, the motion trajectory and attitude of the detector are obtained, and the center line and direction information of the pipeline are calculated.

IMU has the advantages of autonomous navigation, independent of any external reference information, strong anti-interference ability and no signal loss, so it is very suitable for long-time automatic operation in the pipeline. Due to the drift during the inertial navigation, the error accumulates with time, and other navigation methods such as GPS or odometer need to be used to correct it. Therefore, the IMU needs a calibration box on the ground to assist positioning during operation.

Based on the high precision coordinate parameters of pipeline centerline, the displacement and deformation of the pipeline induced by frost heaving and thawing, landslide, settlement and debris flow can be effectively identified, and the curvature of the pipeline and the bending strain related to curvature changes can be evaluated [93-94].

Through carrying the IMU by the geometric detector or MFL detector to obtain the pipeline centerline, and the pipeline bending strain area can be identified through the later data calculation and evaluation. This technology has been applied in pipeline inspection since the 1990s, and is relatively mature now. Through technical cooperation between the Pipeline Company and the Third Institute of Aerospace Science and Technology Group, the high-precision IMU was developed for the first time in China to detect the bending strain of pipeline. The inspection and identification threshold and change threshold reach 0.125% and 0.02% respectively, which are equivalent to the international advanced level.
Magnetostriction is an inherent characteristic of ferromagnetic materials[95]. When ferromagnetic materials are subjected to external force, their internal microstructure will change, and the characteristic parameters such as permeability and conductivity will also change accordingly. By using magnetostrictive effect and its inverse effect, the stress on the materials can be measured indirectly by measuring the change of material permeability.

ACSM is developed on the basis of ACFM[96-97], which uses the magnetostrictive effect of ferromagnetic materials for non-destructive stress measurement. It has low requirements for material surface cleanliness, no coupling required, and a certain lift-off value allowed[98-99]. Its inspection depth is relatively shallow, generally can only measure the stress within the depth of 3mm from the surface of metal materials, but compared with other stress measurement methods, the it has obvious advantage in measuring speed, which is suitable for rapid screening measurement. At present, as one of the main techniques of stress magnetic measurement, this technique has been successfully applied to the stress measurement of bridges, rails and other structures[100].
Baker Hughes and Eddyfi have jointly developed a special probe for in-pipeline inspection, which has been used in the actual inspection project of Baker Hughes. 57 times of in-pipeline inspection has been carried out and more than 7000 Km oil and gas pipelines detected.

![Axial Stress In-line Inspection Probe.](image)

**Figure 18** Axial Stress In-line Inspection Probe.

### 5. In-line Inspection Method of Pipeline Girth Weld
The three main factors leading to the failure of girth weld are weld defect, weld performance and load at weld[101]. How to realize the inspection of these three is the main focus of the weld in-line inspection technology. Aiming at the comprehensive inspection of pipeline girth weld and pipe body, the girth weld in-line inspection technology should be a platform or system integrating multi sensing technologies of pipeline comprehensive condition inspection, that is, the inspection technologies of electromagnetic eddy current, geometric deformation, residual and additional stress should be highly integrated on the basis of the triaxial high-definition MFL, EMAT, crack ultrasonic inspection and other defect inspection sensing technologies, to give play to the complementary advantages of different inspection technologies, forming a new method for girth weld inspection of gas and liquid pipelines.

![Pipeline girth weld inspection technology route.](image)

**Figure 19** Pipeline girth weld inspection technology route.

Volumetric defect + crack defect: research on weld volumetric defect (opening > 0.2mm) by ultra-high-definition MFL inspection, develop circumferential crack ultrasonic inspection (EMAT for gas pipeline) and electromagnetic eddy current inspection to detect the defects with opening less than 0.2mm and non-opening cracks, and improve the defect inspection rate and identification accuracy by the complementarity of various inspection signals.

Material properties: skew welding joint and wall thickness transitioning state can be detected by high-precision geometric inspection, which can be combined with defect inspection information to improve the defect identification rate, and the comprehensive evaluation and analysis of material properties can be carried out by combining with construction characteristics information.

Stress measurement: IMU is adopted for bending stress inspection; ACSM is adopted for axial stress inspection.
6. Conclusions

Based on the analysis of the main failure factors of girth weld of oil and gas pipelines, this paper systematically summarizes the principles and methods of in-line inspection technologies of girth weld defects and additional stress, and puts forward a special inspection scheme of girth weld of oil and gas pipelines, which provides practical reference for the intrinsic safety of oil and gas pipeline at home and abroad. The conclusions are as follows:

1) These three main factors leading to the failure of girth weld of oil and gas pipeline are: weld defect, weld performance and load at weld. How to realize the inspection of these three is the main focus of the weld inspection technology.

2) For oil and gas pipeline girth weld defect inspection, triaxial high-definition MFL inspection technology can effectively detect volumetric defects, but the quantitative accuracy of defect size is not high. And the triaxial high-definition MFL inspection technology and liquid ultrasonic inspection technology cannot effectively detect non-opening crack defects. The inspection rate of planar crack defects can be further improved by using ultra-high-definition triaxial MFL inspection technology.

3) Improving the existing EMAT, electromagnetic eddy current and ACFM inspection technologies is an important future development direction to realize the effective inspection of girth weld crack defects in the future.

4) The inertial navigation inspection based on high-precision IMU can effectively detect the bending strain of pipeline; the ACSM technology based on material magnetostriction inspection is an important method of axial stress measurement at present.

5) Girth weld in-line inspection technology should be a platform or system integrating multi sensing technologies of pipeline comprehensive condition inspection. We should improve and combine of the existing inspection technologies and develop new inspection methods to formulate a targeted inspection method for girth welds.

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Conflicts of Interest

The authors declare no conflict of interest.

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