A COMPREHENSIVE REVIEW ON FAILURE ANALYSIS OF ELECTROFUSION JOINT FOR PLASTIC PIPES

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ABSTRACT

Electrofusion joint plays an important role in connecting plastic pipes and composite pipes. The safety of electrofusion joint has been of major concern affecting the pipeline system. Existing researches reveal that the failure of electrofusion joints is influenced by intrinsic factors such as welding and installation qualities, and external factors such as various load conditions. The combination of these factors would result in different failure modes of electrofusion joints. This paper provided a comprehensive review of current publications on failure analysis of electrofusion joints focusing on both the intrinsic and external factors. The former summarized premature failure of joints caused by incorrect production procedure before service, while the latter addressed the relation between failure modes and load conditions. Key factors affecting the failure modes were subsequently listed. Ultimately, based on current researches and industry hotspots, prospects on the development of electrofusion joint were discussed.

Keywords: electrofusion joint, failure modes, load conditions, failure analysis

1. INTRODUCTION

Electrofusion joint has been widely used in the connection of plastic pipes and composite pipes such as reinforced thermoplastic pipes (RTP), due to its good corrosion resistance, convenient connection and high reliability. A typical structure of electrofusion joint is shown in FIGURE 1. The joint consists of an electrofusion fitting and two plastic pipes inserted from both sides, where the fitting is pre-embedded with a spiral conductive copper wire. After the fitting is connected to a welding machine, heat is generated in the copper wire and then diffuses into the surrounding material to melt it. The melting region expands to the interface in between pipes and fitting, and melts two parts together. After the melting region completely cooling down, the joint is formed with a specific strength.

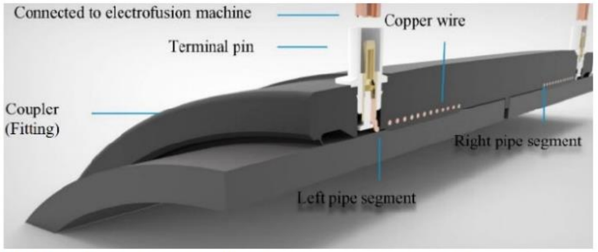


FIGURE 1: SCHEMATICS OF A CROSS SECTION OF AN ELECTROFUSION JOINT [1]

Investigations show that the safety of plastic pipeline system mainly depends on the quality of welding joints, since the manufacturing technology of pipes are relatively stable and mature. According to the PPDC (Plastic Pipe Database Committee) latest 2020 status reports [2], 69.7% of polyethylene pipeline system failures or leaks were due to problems with joints (13.0%) and fittings (56.7%). For this reason, improving the safety and reliability of electrofusion joint is crucial to ensure the healthy operation of the pipeline system.

The safety issues of electrofusion joint are generally affected by various factors, which include appropriate design (including structural parameters and types of joint), correct procedure before welding (including sufficient pretreatment of fusion surface and well installation), suitable welding parameter (including proper welding current, voltage and time), different load conditions arising from service and material properties. The above issues will result in different failure modes of the joint.

This work sorted out different failure modes, load conditions and corresponding failure analysis of electrofusion joints. Key factors affecting the failure modes under different load conditions were discussed and summarized to account for failure analysis of electrofusion joint. The aim of this paper is to provide a reference for establishing a standard procedure for the design and analysis of electrofusion joints based on failure modes.

2. FAILURE MODES OF ELECTROFUSION JOINT

Researches have investigated and classified different failure modes of electrofusion joint in detail. Qi [3] tested the failure of electrofusion joint with different welding structure, and proposed three main failure modes which were fusion area failure, fitting failure and pipe failure. Shi [4], on that basis, tested the joint with different welding parameters, and further subdivided the fusion area failure into fusion interface failure and copper wire interface failure. Engineering cases and experimental results showed that the general failure mode of electrofusion joints was one or several combinations of the above four failure modes.

- **Fusion interface failure**

The reason for fusion interface failure is generally due to the low fusion interface strength. In this case, crack starts from inner cold zone and propagates along the fusion interface in between pipe and fitting to the outer cold zone. The specific failure mode is shown in FIGURE 2(a).

- **Copper wire interface failure**

The reasons for copper wire interface failure can be concluded as: on the one hand, the copper wire reduces the region of plastic material, which can transfer shear stress; on the other hand, the existence of copper wire causes structure discontinuity, which makes the stress state generally higher in this area. In this case, the crack starts from inner cold zone, first propagates to the nearest copper wire, then penetrates through the copper wire interface, and finally extends to the outer cold zone. The specific failure mode is shown in FIGURE 2(b).

- **Fitting failure**

The mode of fitting failure, as shown in FIGURE 2(c), can be further divided into ductile fracture and crack propagation based on the failure morphology [5]. The ductile fracture usually occurs under high stress level condition. At this time, plastic deformation appears in the whole or part of the fitting, which is accompanied by the reduction of the wall thickness. While the crack propagation usually occurs under low stress level condition. At this time, the crack identically starts from inner cold zone, first propagates to the nearest copper wire, and then continues to propagate from the copper wire at a certain angle until the crack completely penetrates through the fitting.

- **Pipe failure**

The mode of pipe failure generally appears near outer cold zone, as shown in FIGURE 2(d). According to the types of pipe, there are mainly two forms of pipe failure during service: pipe fracture and bulging deformation. Pipe fracture occurs when using traditional plastic pipe, and the failure is accompanied by obvious plastic deformation with the reduction of wall thickness. While bulging deformation occurs when using RTP. The failure phenomenon can be described as the interface debonding between reinforced structure and matrix, and the reinforced structure is pulled away from the end of the pipe, contributing to obvious bulging deformation near the joint.

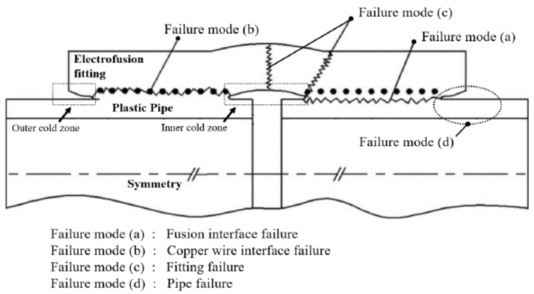


FIGURE 2: FAILURE MODES OF ELECTROFUSION JOINT [4]

3. LOAD CONDITIONS IN DIFFERENT SCENARIOS

Electrofusion joint will be subjected to different types of load conditions in service, which are summarized as follow:

Internal pressure: caused by the working pressure of the pipeline. For the pipeline where an end cap or elbow is near the joint, the internal pressure will bring about equivalent axial stress; For the long and straight pipeline, the pipe can be regarded as plane strain state, where the axial stain is usually neglected.

Water hammer: presented as maximum pressure occurring in pipelines caused by unsteady flow [6], the maximum pressure caused the equivalent stress can be calculated by the Joukowski equation.

Fatigue loads: caused by fluctuations in pressure and the operation of pumps and valves [7].

External pressure: generally adapted in buried pipes, which is basically caused by the installed depth, soils, ground water and traffic load [6].

Bending loads: generally adapted in pipe gallery or construction situation, where the pipeline is likely to bend, and buried pipes suffered from uneven settlement of foundation.

Thermal loads: caused by the temperature discrepancy between the transporting medium and external environment, and temperature variation during service.

Other load conditions: caused by exception, such as point load, impact load, seismic load, uniaxial tension (including dragging load [8] under construction) and etc.

4. FAILURE ANALYSIS OF ELECTROFUSION JOINT

4.1 Intrinsic factor

Researches have shown that premature failure of electrofusion joint in service would occur if the correct production procedures [9] were not followed. The main causes included lack of fusion surface preparation, installation errors and cold welding & over welding, and they were namely summarized as intrinsic factor. The defects, consequences and solutions of the intrinsic factor are listed in TABLE 1.

- **Lack of fusion surface preparation**

Many studies have reported that fusion surface preparation before electrofusion welding could improve welding quality and the performance of electrofusion joint. On the contrary, when there were contaminations on fusion surface or residual oxide layer on pipe surface, the integrity of electrofusion joint would be greatly reduced.

To study the influence of contamination as shown in FIGURE 3(a), Mike [10] and Tayefi [7, 11] prepared the electrofusion joint specimens containing sand and talc contaminations after eliminating the influence of oxide layer. Then short-term hydrostatic pressure test, 80°C hydrostatic pressure test, fatigue test and peel decohesion test were conducted respectively in order to investigate the performance discrepancy between the sound joint and the joint containing contaminations. The test results revealed that contamination obviously diminished the pressure resistance especially long-term pressure resistance and interface strength of the joint. The tests also verified that various contaminations would have different diminishment on joint performance.

Mike [10] and Tayefi [7, 11] also reported that oxide layer had similar effects with contaminations on joint. The results showed that the reduction of pressure and peeling resistance caused by oxide layer was less than that caused by contaminations. Lowe [12] also quantitatively analyzed the cleavage energy of the joint with talc contamination and oxide layer, which was 85% and 50% lower than best practice condition. In the treatment of the oxide layer, Boge [13] carried out a variety of treatment methods on the outer surface of pipe, such as scraping and cleaning only (with water, ethanol and heptane). The device for scraping oxide layer was shown in FIGURE 3(b). Vanspeybroeck [14], on this basis, proved that only a small scraping depth (less than 0.1 mm) could obtain better joint performance. Bowman [15] also proposed that the maximum scraping amount should be strictly controlled, since overscraping could increase the gap between pipes and fitting, subsequently there was a risk that the joint would not be formed after welding.

(a) Typical contamination [10] (b) Scraping of oxide layer [12]

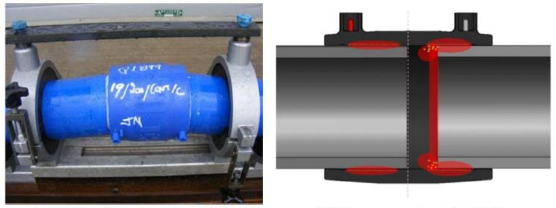
FIGURE 3: CONTAMINATION AND SCRAPING OF OXIDE LAYER

- **Installation errors**

Installation errors of pipes and fitting can be divided into misalignment and incorrect stab. The installation errors will directly affect welding quality and performance of the electrofusion joint.

For the error of misalignment, Lowe [12] proposed that misalignment, on the one hand, caused obvious gap between pipes and fitting, which would affect heat transfer during welding process. On the other hand, it was likely to contribute to the dislocation of copper wire as well, which would have a negative influence on welding quality. For the error of incorrect stab, where one or both of the pipe ends were not centered in the fitting, several reports [16] proposed that due to the shortening or even disappearance of inner cold zone, melt flow would drive the copper wire moving. In serious cases, the copper wire would dislocate and self-contact was likely to occur, which resulted in severe over welding or even unable to weld.

There are few reports investigating the influence of installation error on the failure of electrofusion joint. This is due to correct installation can arguably be realized by the implementation of appropriate tooling and training [7], and hence negative consequence form the installation error can be effectively eliminated.



(a) Misalignment [12] (b) Incorrect stab [16]

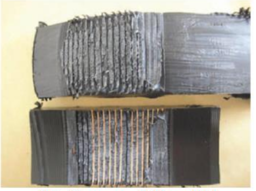
FIGURE 4: INSTALLATION ERRORS

- **Cold welding & over welding**

Considering the influence of welding process on the quality of electrofusion joint, Shi [17, 18] proposed that common welding defects could be divided into cold welding and over welding. The former was usually caused by insufficient welding time or welding power, while the latter was caused by excessively high temperature around the copper wire due to too much input energy, which would result in material degradation and generation of voids close to this region. Both of the welding defects would weaken the performance of joint seriously.

Researchers generally prepared the electrofusion joint with cold welding and over welding defects by adjusting the welding time. Standard test such as long-term hydraulic pressure test and peeling test were carried out to investigate the failure of the joint under inadequate welding process. For the cold welding defect, the predominant feature was observed as significant strength reduction on fusion interface, where the failure was prone to occur. Concretely, pressure test results revealed the premature failure of electrofusion joint was due to the crack propagation through fusion interface and eventually lead to the leakage [4], when the joint was made with welding time of 30% and 40% of specified fusion time (SFT). Peeling test results presented brittle-dominant failure in fusion surface [4, 15] as shown in FIGURE 5(a), and the peeling strength and peeling energy regularly decreased with the welding time [19]. For the over welding defect, it mainly resulted in ductile-dominant failure on copper wire interface as shown in FIGURE 5(b). As the welding time further increased, obvious ductile-brittle transition on the copper wire interface occurred [19], which proved that the material has degraded and the performance of joint would be reduced. Ultimately, for the joint made under SFT, the strength of welding zone including fusion interface and copper wire interface presented significant enhancement. Following above tests, the results showed all the failures occurred at pipe or fitting as shown in FIGURE 5(c).

(a) Cold welding [4]



(b) Over welding [4]

(c) Joint made under SFT [13]

FIGURE 5: FAILURE MODES INFLUENCED BY WELDING DEFECTS

TABLE 1: INFLUENCE OF INTRINSIC FACTOR AFFECTING THE FAILURE OF ELECTROFUSION JOINT

Intrinsic factor	Defects	Consequences	Solutions
Lack of fusion surface preparation	Contaminations	1. Diminishment on fusion strength; 2. Premature failure probably occurs on fusion interface under various load conditions; 3. Diminishment on joint performance is related to the types of contaminations …	Scraping the pipe properly and ensuring the cleanliness of the fusion surface
	Oxide layer	1. Diminishment on fusion strength; 2. Premature failure probably occurs on fusion interface under various load conditions; 3. Diminishment on joint performance is less than that caused by contaminations …	
Installation errors	Misalignment	1. Dislocation of copper wire; 2. Uneven heat transfer during welding process; 3. Hard to form electrofusion joint …	Implementation of appropriate installation tooling and training
	Incorrect stab	1. Exceptional melt flows; 2. Dislocation of copper wire; 3. Over welding in local area; 4. Hard to form electrofusion joint …	
Cold welding & over welding	Cold welding	1. Diminishment on fusion strength; 2. Premature failure probably occurs on fusion interface under various load conditions; 3. Brittle fracture dominates the failure on fusion interface …	Establishing adequate welding current, voltage and time for specific electrofusion joint
	Over welding	1. Degradation of material; 2. Generation of voids near the copper wire; 3. Ductile fracture dominates the failure on copper wire interface …	

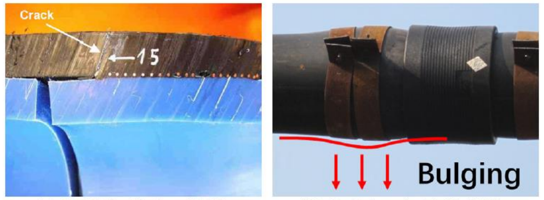
4.2 External factor

The influence of load conditions on electrofusion joint can be summarized as external factor. Existing researches have qualitatively analyzed the failure modes under different load conditions by means of direct or indirect tests. This section summarized the failure analysis of electrofusion joint affected by external factors, as listed in TABLE 2. Key factors directly related to failure and applicable service condition were put forward accordingly.

- **Internal pressure**

Internal pressure is the most common load of electrofusion joint. Researches have studied the failure modes of electrofusion joint under different type of internal pressure, including sustained hydraulic pressure test, short-term burst test and dynamic pressure test. Meanwhile, according to specific requirements, the tests would also be conducted under different temperature. Due to the rate-dependent and temperature-dependent properties of plastic material, electrofusion joint would present different failure modes.

In order to investigate the failure under long-term service such as 50 years [20, 21], sustained hydraulic pressure test according to ISO 4437 was generally conducted. The test results showed different failure modes when using different types of pipes. When traditional plastic pipe was introduced to the joint, the failure mode was generally dominated by slow crack growth (SCG) [4, 10, 22], which initiated from the first copper wire closest to cold welding zone, and penetrated through fitting with an angle of about 70° with axial direction. The results also presented obvious brittleness at the crack, as shown in FIGURE 6(a). Zheng [23] studied the failure mechanism and concluded that the equivalent axial stress caused by internal pressure was the key factor affecting crack initiation. Zhang [24] further found the crack initiation and propagation were predominately controlled by mode II and mode I crack, respectively. A critical J-integral value was also provided to predict the crack propagation. When FRP was introduced to the joint, bulging failure appeared to be the main failure mode after long-term bearing, where the bulging generally occurred at the end of FRP. Zhang [25, 26] and Shi [27] subdivided the failure process into three stages: interfacial debonding, interfacial sliding and ultimate bulging. They subsequently proposed that the key factor for the bugling failure was the shear stress on the interface in between reinforced structure and matrix. The shear stress was induced by the transfer of equivalent axial stress between pipe and fitting. Once the shear stress exceeded shear strength, it may lead to the debonding of interface and contributed to the bugling failure.

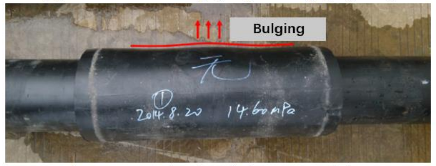


(a) SCG in fitting [10] (b) Bulging in FTP [27]

FIGURE 6: FAILURE MODES UNDER LONG-TERM SERVICE

In order to investigate the failure modes of EF joint under short-term load such as water hammer, researchers carried out short-term burst test according to ISO 1167. The test results were also varied from the types of pipes. For the joint with plastic pipe, the burst failure was dominated by ductile fracture in pipe, and the fracture position was closed to outer cold zone, as shown in FIGURE 7(a). Nie [28] reported the equivalent hoop stress caused by internal pressure would concentrate and become the main factor of burst failure. For the joint with RTP, the burst results presented ductile fracture in joint, accompanying with obvious bulging and deformation, as shown in FIGURE 7(b). For the failure mechanism, Nie illustrated both internal pressure and its equivalent axial stress were main factors contributing to the failure. The internal pressure induced bulging from inner cold zone, while the tensile effect from equivalent axial stress resulted in the reduction of wall thickness in the middle of the fitting.

(a) Fracture in the pipe (plastic pipe joint)



(b) Fracture in the fitting (RTP joint)

FIGURE 7: FAILURE MODES UNDER SHORT-TERM SERVICE [28]

When the joint was under fatigue pressure service, fatigue crack propagate through fitting was the main failure mode, and fatigue life was related to the amplitude and frequency of internal pressure [7, 29]. At this time, equivalent cyclic axial stress was considered to be the main factor accounting for the fatigue failure.

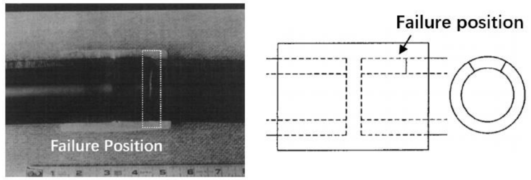
- **External pressure**

The electrofusion joint would bear both the internal pressure from medium, and the external pressure from soil. Berger [22] demonstrated that the failure was also dominated by SCG, and the failure morphology and mechanism were both similar with that in pure internal pressure. The investigation further proposed that the external pressure would reduce the effect of equivalent axial stress, and the stress intensity factor of inner cold zone would hence reduce. Therefore, it was indicated that the joint under internal pressure accompanying with appropriate external pressure would present a more conservative service life.

- **Bending load**

Bending is ubiquitous in both service and construction stages of electrofusion joint. So far, researchers based on experimental methods such as four-point bending [30] and pure bending [31], carrying out bending fatigue test to evaluate bending performance and failure modes of the joint.

In construction stage, when the joint was not yet subjected to internal pressure, the bending resistance was severely weakened, and the bending fatigue life was reported to decrease by 97.6% as compared with pipe [30]. Bending stress, as a key factor, mainly affected the structure near outer cold zone, where premature failure was likely to appear, as shown in FIGURE 8. In service stage, when the joint was under internal pressure, the bending fatigue life would slightly increase, but remained relatively low. Therefore, additional bending loads should be strictly avoided, regardless of load conditions.



(a) Test results (b) Schematic diagram

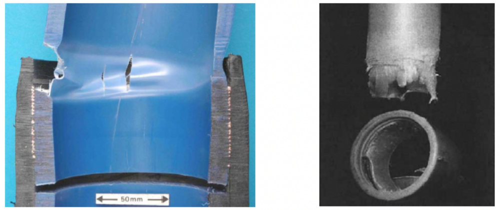
FIGURE 8: FAILURE MODES UNDER FATIGUE BENDING LOAD [30]

- **Thermal load**

Alizadeh [32] analyzed the influence of thermal load based on the condition where the temperature of medium was higher than that of environment, and proposed the thermal load could effectively reduce the stress intensity factor on inner cold zone and played a role in crack closure. Reza [33] also analyzed that the thermal load from positive temperature variation significantly reduced the axial stress and Mises stress at joint, which would improve the safety of joint. However, it should be emphasized that although above studies have proved that appropriate temperature rise could improve the safety of electrofusion joint in service, higher temperature would cause risks of material aging, thereby degrading the joint performance.

- **Other loads**

The failure analysis under other load conditions has also been reported. In order to study the failure modes of joint when subjected to uniaxial tensile load, whole pipe tensile creep rupture test [10] and tensile test [34] were carried out accordingly. Long-term and short-term tests results both revealed that the fracture was occurred at the end of the pipe, as shown in FIGURE 9. Hence, it could be inferred that when the joint was subjected to uniaxial tensile load, the premature failure was due to the structure particularity of outer cold zone, which contributed to the stress on the pipe exceed its strength.



(a) Tensile creep rupture test [10] (b) tensile test [34]

FIGURE 9: FAILURE MODES UNDER UNIAXIAL TENSILE LOAD

TABLE 2: INFLUENCE OF EXTERNAL FACTOR AFFECTING THE FAILURE OF ELECTROFUSION JOINT

External factor	Load conditions	Types of joint	Failure modes	Key factors	Service conditions
Internal pressure	Sustained hydraulic pressure test	Plastic pipe joint	SCG in fitting	Equivalent axial stress & Fracture toughness of mode I-II crack at joint	Service life cycle (50 year), high temperature or long-term creep conditions
		RTP joint	Bulging in RTP	Equivalent axial stress & Shear strength of the interface in between reinforced structure and matrix	
	Short-term burst test	Plastic pipe joint	Ductile fracture in pipe closed to outer cold zone	Equivalent hoop stress & Strength of pipe	Water hammer, pressure boosting, and other short-term conditions
		RTP joint	Ductile fracture in joint	Equivalent axial stress & Strength of fitting	
	Fatigue pressure test	Plastic pipe joint	SCG in fitting	Amplitudes and frequency of pressure & Equivalent cyclic axial stress & Fatigue resistance of fitting	Fluctuations in pressure
External pressure	External pressure test with pressurized joint	Plastic pipe joint & RTP joint	SCG in fitting (less risky than pure internal pressure)	Value and ratio of internal and external pressure & Fracture toughness of mode I-II crack at joint	Buried pipeline, and other external pressure conditions
Bending load	Bending fatigue test with non-pressurized joint	Plastic pipe joint & RTP joint	Fracture in pipe closed to outer cold zone	Amplitudes and frequency of bending load & Bending fatigue resistance of joint	Overhead pipeline (pipe gallery), abnormal bending in construction or service
	Bending fatigue test with pressurized joint		Fracture in pipe closed to outer cold zone (less risky than non-pressurized joint)	Amplitudes and frequency of bending load & Bending fatigue resistance of joint & Value and ratio of internal pressure and bending load	
Thermal load	Sustained hydraulic test with temperature gradient or variation	Plastic pipe joint & RTP joint	SCG in fitting (risk related to temperature gradient)	Temperature distribution and variation & Equivalent axial stress & Fracture toughness of mode I-II crack at joint	Temperature discrepancy between medium and environment, temperature variation
Other loads	Whole pipe tensile creep test	Plastic pipe joint	Fracture in pipe closed to outer cold zone	Uniaxial tensile load & Strength of pipe	Dragging condition
	Tensile test				

5. FUTURE OUTLOOKS

At present, plastic pipeline system is developing towards high pressure conditions and large diameters. Therefore, it is important to developed appropriate method to improve the performance of joint. So far, improving the safety of electrofusion joints is mainly considered from multiple aspects, such as optimum welding strategy, material modification, structure optimization and more comprehensive testing on joints.

From the perspective of welding process, cold welding and over welding are the most serious welding defects, which need to be resolved urgently. So far, studies [35-37] have implemented thoroughly analysis of the temperature field of joints during welding process. Based on this, if an optimum welding strategy can be proposed, then sufficient heat input can be ensured while the maximum welding temperature can be controlled during welding process, subsequently cold welding and over welding will be both avoided.

From the perspective of material modification, it is considered that when the material of fitting has higher strength and fracture toughness, the electrofusion joint has a correspondingly higher bearing capacity. Existing studies have reported that materials can be reinforced by filling fibers [38], reinforcing particles [39], etc. into plastic matrix. Yao [40] presented the burst pressure of reinforced joint was increased by 41.8%, when the fitting was produced by chopped carbon fiber reinforced polyethylene (CFRP). Based on material modification, self-monitoring can be realized as well, and the safety of joint can be actively monitored. Hence, material modification has beneficial effects in terms of joint performance enhancement and safety assurance.

From the perspective of structure optimization, since inner cold zone, outer cold zone and pre-embedded copper wire are risky structures where failure is likely to occur. A reasonable structural design of fitting such as the embed depth and winding technique of copper wire can reduce the influence of these risky structures on failure. Meanwhile, for complex working environments, new types of electrofusion fitting with higher performance need to be designed and further developed [41].

6. CONCLUSION

This paper provided a review for failure analysis of electrofusion joint, and the following conclusions were drawn:

(1) Four types of failure modes of electrofusion joints and different load conditions in service were summarized.
(2) The relationship between failure modes and load conditions was discussed, and key factors affecting the failure modes were listed.
(3) The prospects of welding process optimization, material modification, and structure optimization were suggested for the development of electrofusion joint.

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