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Risk assessment of electrofusion joints in commissioning of polyethylene natural gas networks

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ABSTRACT

The application of polyethylene pipes and equipment in the natural gas networks is continuously increasing due to their competitive weight and cost compared to metallic materials. Electrofusion welding is an effective and fast approach for the production of polyethylene joints with high safety and endurance. However, recently intermittent failures have reported in underground polyethylene piping networks. Although the failure frequencies are low, but disasters could happen due to the failure in gas pipelines as they usually buried in populated areas. In this study a combination of Failure Mode and Effects Analysis (FMEA), and empirical methods were used to identify main damage mechanisms incorporated to intermittent failures of polyethylene natural gas networks. After performing the FMEA process, based on the obtained risk ranking, three most critical damage mechanisms, including improper scraping, lipid contaminations, and humidity existence in weld zones were investigated experimentally to determine their practical severity. According to empirical evaluations, improper scraping was the most severe damage mechanism, followed by the contaminated welding surfaces during the weld construction.

1. Introduction

Polyethylene pipes (PEPs) for natural gas network applications have first been used in the USA in the late 1950s and got interested in Europe after 1970s [1]. PEPs and equipment used in gas networks are cost-effective, non-toxic, resistant to corrosion and have increased life cycle (about 100 years) [2]. In a study by Bachir-Bey et al. [3], some portions of PEPs were cut after almost 30 years of operation and no sign of aging in terms of mechanical properties were observed. However, intermittent failures in this type of piping networks have been reported in different countries. The failures statistical data of a natural gas network in the USA between 2004 and 2015 were investigated by Bianchini et al. [4] indicating frequency of accidents of about 2.09×10^{-5} failures per kilometer per a year. Additionally, they found that the average number of injuries and fatalities in low-pressure small diameter natural gas systems is even higher than high-pressure-large diameter piping networks.

The most critical threat to the integrity of polyethylene piping systems is a leakage from electrofusion joints. In contrary to steel pipes, non-destructive evaluation (NDE) of PEPs is a challenging task. Recently, researchers attempted to employ a combination of artificial intelligence and traditional NDE methods to determine defects in electrofusion joints [5,6]. In addition to NDE limitations, the main problem in the design of electrofusion joints is lack of comprehensive knowledge on PEPs physicochemical characteristics that affect their mechanical behavior and performances. For instance a crack growth as one of these challenging issues is under investigation by several researchers [7,8]. Recent reports showed that the failures normally occur due to micro-cracks initiation at the interface of a pipe and coupler, where subsequent growth of micro-cracks leads to a brittle fracture [7,8].

It has been reported that the main reason for most of failures in electrofusion joints could be related to application of low-quality materials and non-standard construction procedures [9]. The source of many defects in electrofusion joints is related to the weld surface

Abbreviations: FMEA, Failure Mode and Effects Analysis; PEPs, Polyethylene pipes; NDE, Non-destructive evaluation; POF, Probability of Failure; COF, Consequence of Failure; PFDs, Piping flow diagrams; P&ID, instrumentation diagrams; SEM, Scanning electron microscope; CT-scans, Computerized tomography scans.

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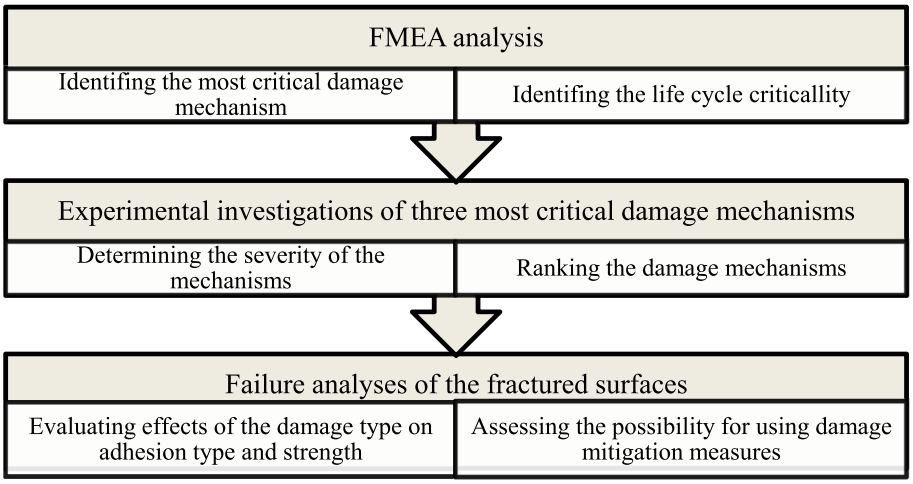

Fig. 1. Flowchart of working steps of current study.

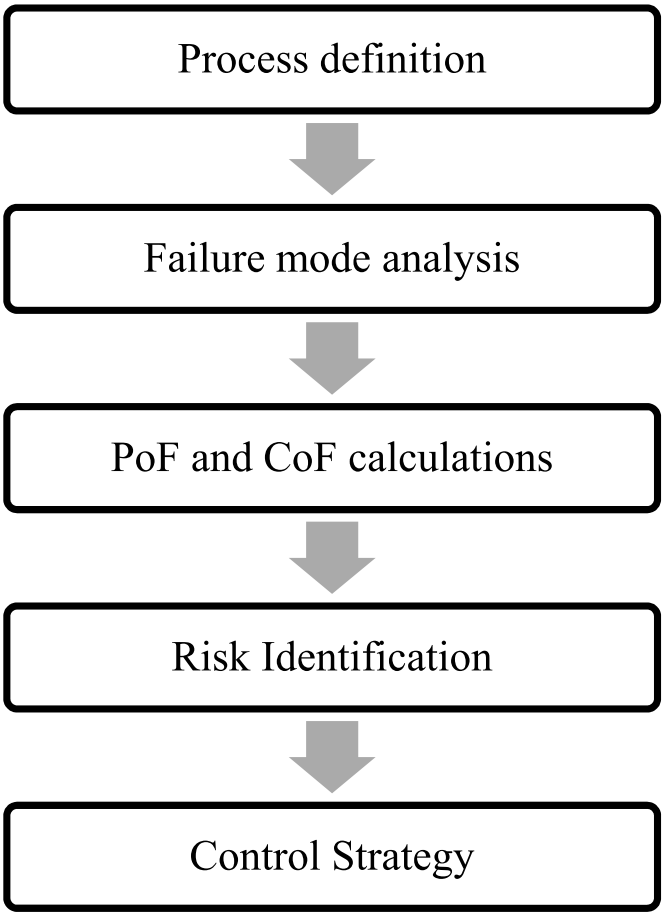

Fig. 2. Flowchart of the FMEA process.

Table 1
Generic POFs (a) for different damages types.

Damage type	generic POFs (a)
Physical damage	1.01×10^{-2}
Poor procurement	1.04×10^{-4}
Humidity at the welding surfaces	1.01×10^{-2}
Improper scrapping	1.2×10^{-2}
Lipid type pollutants	1.02×10^{-2}
Misalignment of the joints	1.03×10^{-3}
Unsuitable welding temperature	1.03×10^{-5}
Equipment failure	1.05×10^{-4}
Shaking and mechanical damages	1.01×10^{-4}
Nonstandard maintenance	1.00×10^{-3}

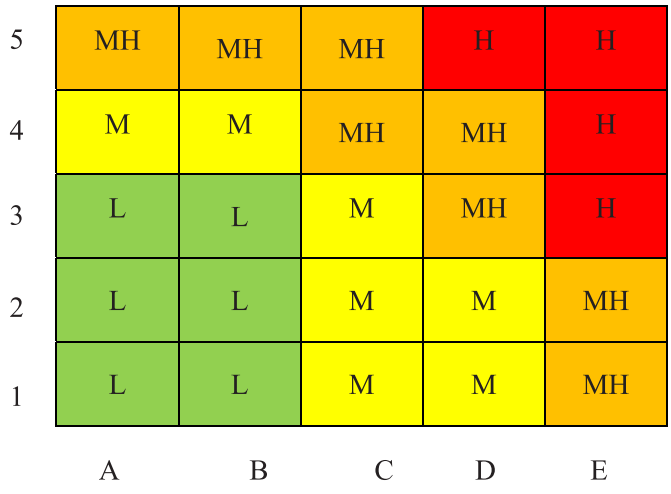

Fig. 3. Risk matrix to combine COFs and POFs.

preparation step and other pre-welding activities during the construction phase. Towards, welders qualification is a crucial factor in achieving high quality joints [10]. The strength of electrofusion joints depends on the welding temperature, dwell time for heating and cooling, cleanliness of the parent surfaces, and the pipe and coupler alignment [11]. The cleanliness of the parent surfaces is a vital parameter and even a small pollutant on the welding surfaces can substantially reduce the joint-life [12]. The scraping of the parent surfaces before the welding not only removes all contaminations from the surfaces, but also removes all oxide layers from the welding region [13]. The oxide layers on the surface of PEPs prevent homogeneous mix-ability of the pipe and coupler melts through the welding process [14]. Therefore, scraping of the pipe surface before the welding process is an essential step to ensure that the contaminations such as pollutants, greases, humidity, and dusts are completely removed from the welding region [15]. To achieve satisfactory welded joints, the welding temperature also needs to be set in a range of technically confirmed high-working-temperature. Researches have shown that the melt pressure at the welding cavity is too low to fill all gaps between the coupler and pipe when welding in

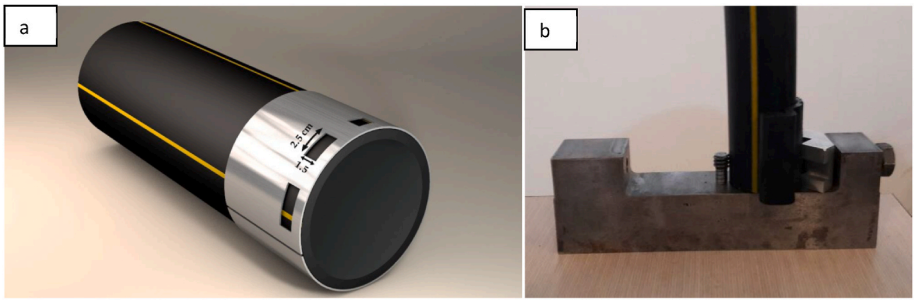

Fig. 4. Apparatus to produce man-made defects in welding zones. (a) Schematic of a stencil for accurate production of lipid pollution and moisture type defects; (b) Apparatus used for the production of improper scraping with dimensions of $35mm \times 15mm$

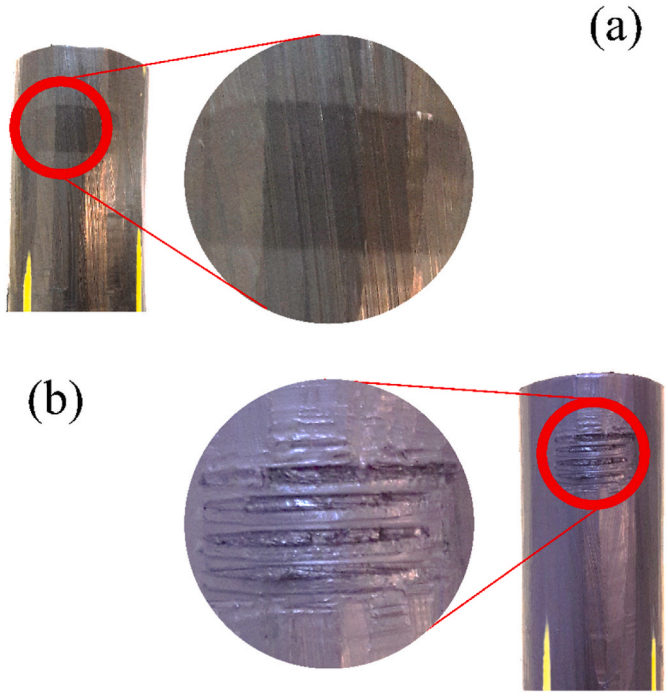

Fig. 5. (a) The lipid type pollutant on a pipe surface before the welding process; (b) Example of improper scraping on a welding surface.

Table 2
Electrofusion welding parameters.

Coupler	Heating time of coupler elements	Initial cooling time	Total Cooling time	Welding voltage
Sample no. 1	93 s	12 min	30 min	38 V

low-temperature regimes [16]. Therefore, weather condition at the time of welding is very important in electrofusion welding process [17]. Recently, Ramadan and Tanase [18] studied the influence of welding parameters on structural integrity of PEPs and concluded that rapid cooling of the welding zone due to a cold weather can be one of the main sources of intermittent failures in PEP pipelines. The effect of pre-heating in the quality of electrofusion joints is investigated by Najafigharehtapeh and Kaçar [19].

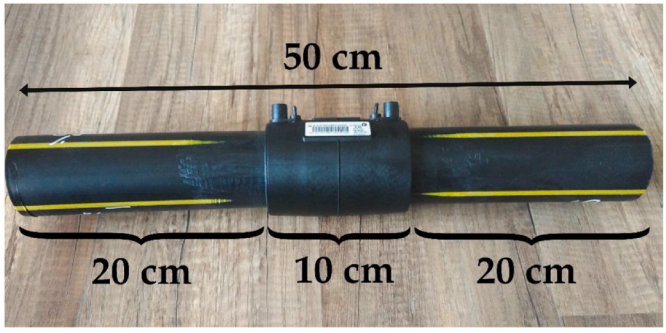

Fig. 6. Final experimental setup for electrofusion welding.

Tutunchi et al. [20] ranked the possible failure mechanisms in the commissioning stage of the urban natural gas systems and determined the most critical locations for monitoring and inspection priority purposes. Review of literatures showed that most of failure modes and imperfection types in PEPs have been presented and studied by many researchers [21,22] However, to the best knowledge of authors there is no risk ranking of imperfections in literatures. This study employed the risk assessment concept to identify root causes of intermittent failures in polyethylene natural gas piping systems. This risk assessment procedure begins with FMEA, which determines the three most critical failure mechanisms in PEPs and continue with empirical analyses, which ranks the highlighted mechanisms based on their severity. Fig. 1 shows the process followed in this work.

2. Process and methodology

2.1. FMEA technique

FMEA is a systematic way of recognizing a failure mechanism in materials and processes [18]. It has many applications in the oil and gas industries. Fig. 2 shows different steps of the FMEA. It includes the following steps:

1 - Process definition: the main goal of this stage is to define the scope of the assessment procedure. It helps to break the whole process down into different phases to make the events manageable. A team of engineers, with various disciplines, including manufacturing, construction, commissioning, and integrity typically are taking part in this step.
2 - Failure mode analysis: in this step, all parameters related to the process (e.g. welding temperature, the pipe surface preparation, and

Table 3
Identification of damage mechanisms- FMEA analysis.

No.	Executive Phase	Failure mechanism	Risk driver
1	Loading and transportation	Physical damage	Unsuitable loading
		Poor procurement	Welding using pipe and coupler from different brands
2	Construction	Humidity at the welding surfaces	Weather condition or other humidity sources
		Improper scrapping	Scrapping using non-standard devices
			Improper scrapping
			Long waiting time between scrapping and welding
		Lipid type pollutants	Unsuitable solution
		Misalignment of the joints	Using non-standard alignment devices
		Other pollutants	Using unsuitable fabric
		Unsuitable welding temperature	Not following standard procedures
		Unsuitable Cooling and warming time	Not following standard procedures
			Insufficient cooling time
			Excess welding time
		Welding equipment fault	Unsuitable voltage
			Unsuitable welding time
		Lack of complete coupling between electrical socket and coupler switche	Defective coupler switches
			Using not calibrated welding device
			Lack of control on output voltage
3	Operation	Shaking and mechanical damages	Lack of protective measures
		cyclic loads especially for small bore branches	Harsh operating condition
		Nonstandard maintenance	Not following the written procedures

etc), operation, construction, and procurement steps, and also the associated damage mechanisms were determined and classified.

3 - Probability of Failure (POF) and Consequence of Failure (COF) estimations: in this step, considering the general failure frequencies in the industry and taking into account the failure history of the component, the PoF and CoF scores for each active damage mechanism were calculated.

4 - Risk identification: in this step, the POF and COF scores for each damage mechanism were combined to calculate the failure risk of the component. Subsequently, damage mechanisms were ranked based on their severity (Fig. 3).

5 - Damage mitigation strategies: based on identified risk categories for each damage mechanism, mitigation techniques such as inspection methods, inspection intervals, and replacement strategies were suggested. The goal of this step was decreasing the failure risk of each active damage mechanism to an amount lower than the target risk level.

A natural gas pipeline network of residential and industrial areas of Urmia, Iran (a 5543 km underground piping system) is made of PEPs mostly in diameters of 90 mm, 63 mm, and 25 mm. The operating pressure of this network is about 0.4 MPa. The highest failure rate has been reported in piping systems with diameters of 25 mm and 63 mm (i.e. 1.3×10^{-3} failure per kilometer per a year).

A risk assessment process was used to identify failure sources, to manage and control the rate of accidents in this network. In this regards, a team of experienced engineers was employed to implement FMEA technique and to determine active damage mechanisms in a polyethylene natural gas piping network of Urmia. Related documents, including piping flow diagrams (PFDs), piping and instrumentation diagrams (P&ID), inspection histories, anomaly record, and other repair

Table 4
Ideal mitigation measures versus average mitigation coefficient (*M*) for the current case study.

Damage Mechanism	Mitigation 1	Mitigation 2	Mitigation 3	Average mitigation coefficient (*M*)
Physical damage	Control on loading	Control on unloading	–	50%
Poor procurement	Qualified purchase order	Vendor reputation	Shop inspection	70%
Humidity at the welding surfaces	Check welding surfaces	Check weather condition	–	20%
Improper scrapping	Check devices	Establish scrapping procedure	Random checks by inspection engineer	40%
Lipid type pollutants	Check cleaner type	Check for pollutant sources	Use clean and non-fluffy fabric for clean the welding surfaces	80%
Misalignment of the joints	Check alignment devices	Control excavation condition	–	90%
Unsuitable welding temperature	Check weather condition	Use pre-heat and post heats	Use tent	20%
Equipment failure	Follow component data sheet	Check welding voltage	Check welding time	20%
Shaking and mechanical damages	Use alarm signs and protective measures in welding area	Use protective measures	Take care of cyclic load on new joints	90%
Nonstandard maintenance	Maintenance procedure	Quality control	Pressure test	100%

Table 5
Possible survivability options versus survivability coefficient (*S*) of case study.

Damage mechanisms	Survivability 1	Survivability 2	Average Survivability coefficient (*S*)
Physical damage	Polyethylene Structural integrity	Pipe diameter	0.8
Poor procurement	–	–	0
Humidity at the welding surfaces	Weldability of the material under humidity	Welding voltage	0.2
Improper scrapping	PE grade fusion capability		0.2
Lipid type pollutants	–	–	0
Misalignment of the joints	Misalignment quality and range		0.5
Unsuitable welding temperature	–	–	0
Equipment failure	–	–	0
Shaking and mechanical damages	Stress concentration factor of the material grade	Number of hours working under cyclic loads	0.4
Nonstandard maintenance	–	–	0

Table 6
Summary of the risk parameters of PEP damage mechanisms for the case study.

Damage mechanism	A	M	S	w_m	w_s	POF	POF category
Physical damage	1.01×10^{-3}	50%	0.8	0.5	0.5	4.55e-04	3
Poor procurement	1.04×10^{-4}	70%	0	0.5	0.5	6.76e-05	2
Humidity at the welding surfaces	1.01×10^{-2}	20%	0.2	0.5	0.5	8.18e-03	4
Improper scrapping	1.2×10^{-2}	40%	0.2	0.5	0.5	7.34e-03	4
Lipid type pollutants	1.02×10^{-2}	80%	0	0.5	0.5	6.12e-03	4
Misalignment of the joints	1.03×10^{-4}	90%	0.5	0.5	0.5	4.25e-05	2
Unsuitable welding temperature	1.03×10^{-5}	20%	0	0.5	0.5	9.27e-06	1
Equipment failure	1.05×10^{-4}	20%	0	0.5	0.5	9.45e-05	2
Shaking and mechanical damages	1.01×10^{-4}	90%	0.4	0.5	0.5	4.44e-05	2
Nonstandard maintenance	1.00×10^{-4}	100%	0	0.5	0.5	5.00e-05	2

Table 7
Five levels of POF.

	POF value	POF category
Highly unlikely	$9.9 \times 10^{-6} > POF$	1
unlikely	$9.9 \times 10^{-6} < POF < 9.9 \times 10^{-5}$	2
Possible	$9.9 \times 10^{-5} < POF < 9.9 \times 10^{-4}$	3
Likely	$9.9 \times 10^{-4} < POF < 9.9 \times 10^{-3}$	4
Very likely	$9.9 \times 10^{-3} < POF$	5

Table 8
Result of the risk assessment for PE piping network of the present study.

Damage mechanism	POF	Detection phase of the project	COF	Risk level
Physical damage	3	Pressure test	B	Low
Poor procurement	2	Pressure test	B	Low
Humidity at the welding surfaces	*4*	*Operation*	*D*	*Medium High*
Improper scrapping	*4*	*Operation*	*D*	*Medium High*
Lipid type pollutants	*4*	*Operation*	*D*	*Medium High*
Misalignment of the joints	2	Operation	D	Medium
Unsuitable welding temperature	1	Pressure test	B	Low
Equipment failure	2	Pressure test	B	Low
Shaking and mechanical damages	2	Operation	D	Medium
Nonstandard maintenance	2	Operation	D	Medium

and maintenance documents were provided prior the brainstorm session for the team members from departments of inspection, maintenance, construction, health and safety. At the session time, besides the twenty years' anomaly report of the Urmia natural gas company, it was asked from each team member to mention own knowledge and experiences regarding active damage mechanisms in each stage of the network lifecycle, individually. Based on the risk ranking of the damage mechanisms, three most critical mechanisms were selected for further experimental evaluations.

The risk assessment team members were asked to determine POF and COF scores for each damage mechanism using tables prepared based on improved *Kent Muhlbauer* formula (Eq. (1)). In Eq. (1) M and S indicate coefficients for the mitigation and survivability parameters, respectively. Furthermore, w_m and w_s are weight factors which balance the effects of the mitigation and survivability parameters, respectively. In this study, both these parameters were set to be 0.5; means equal effect of mitigation and survivability factors. In addition, in Eq. (1) the unit of a is failure per year per kilometer and represents a generic POF value of the damage mechanism and equals the failure frequency due to that specific damage type based on historical failure records. Table 1 shows generic POFs for different damage mechanisms based on twenty years' failure reports of the Urmia natural gas pipeline.

$$POF = a \times (1 - w_m \cdot M) \times (1 - w_s \cdot S) \tag{1}$$

Mitigation coefficient (M) reflects the effect of the type and effectiveness of every mitigation measure designed to block or reduce an exposer. A subject matter engineer compared the ideal mitigation measures with available mitigation measures at the system and estimated the mitigation coefficient (M) for damage types. On the other hand, survivability (S) is the inherent ability of a piping material to sustain forces and deformations in the event of mitigation failure. The construction materials and fabrication quality dictates the value of the S parameter. The risk assessment team listed all potential abilities of the used material to sustain against each exposer. The appraisal decided how much percent of the ideal survivability has been satisfied in current piping system. In order to reduce the effect of human bias and avoid the influence of artificial preferences the average coefficient determined by three or more experts, as per Eq. (2), was used for POF and COF calculations.

$$M = \frac{\sum_{i=1}^{n} m_i}{n} \tag{2}$$

where, n is the number of appraisers, and m_i is the mitigation coefficient estimation of appraiser number i. After determination of POFs and COFs, the risk level of damage mechanisms were determined. In this study risk matrix as Fig. 3 was used to combine POFs and COFs.

2.2. Experimental methodology

In the empirical part of this study, polyethylene pipes (grade of PE-100-SDR11) with outer diameter of 63 mm in lengths of 500 mm were supplied by local vendors in sufficient numbers. The required numbers of couplers were supplied by the same company. Before the welding, samples were scraped using a scraper in accordance with the written procedure, then samples were cleaned using acetone solution (98%) and a piece of fabric. The equipment specifications of used technique were satisfied the requirements of the electrofusion welding procedure and the requirements specified by the material vendor.

In order to investigate the effects of various defects in the final joint quality, several artificial defects at the welding zones were created. To preserve data validity and experiments repeatability, an aluminum foil as stencil was used according to Fig. 4(a) to artifact aimed defects. However, defects in type of "non-scraped regions" were fabricated using the method presented in Fig. 4(b). Samples with properly scrapped surfaces using a standard scraping device were also prepared and used as the control group.

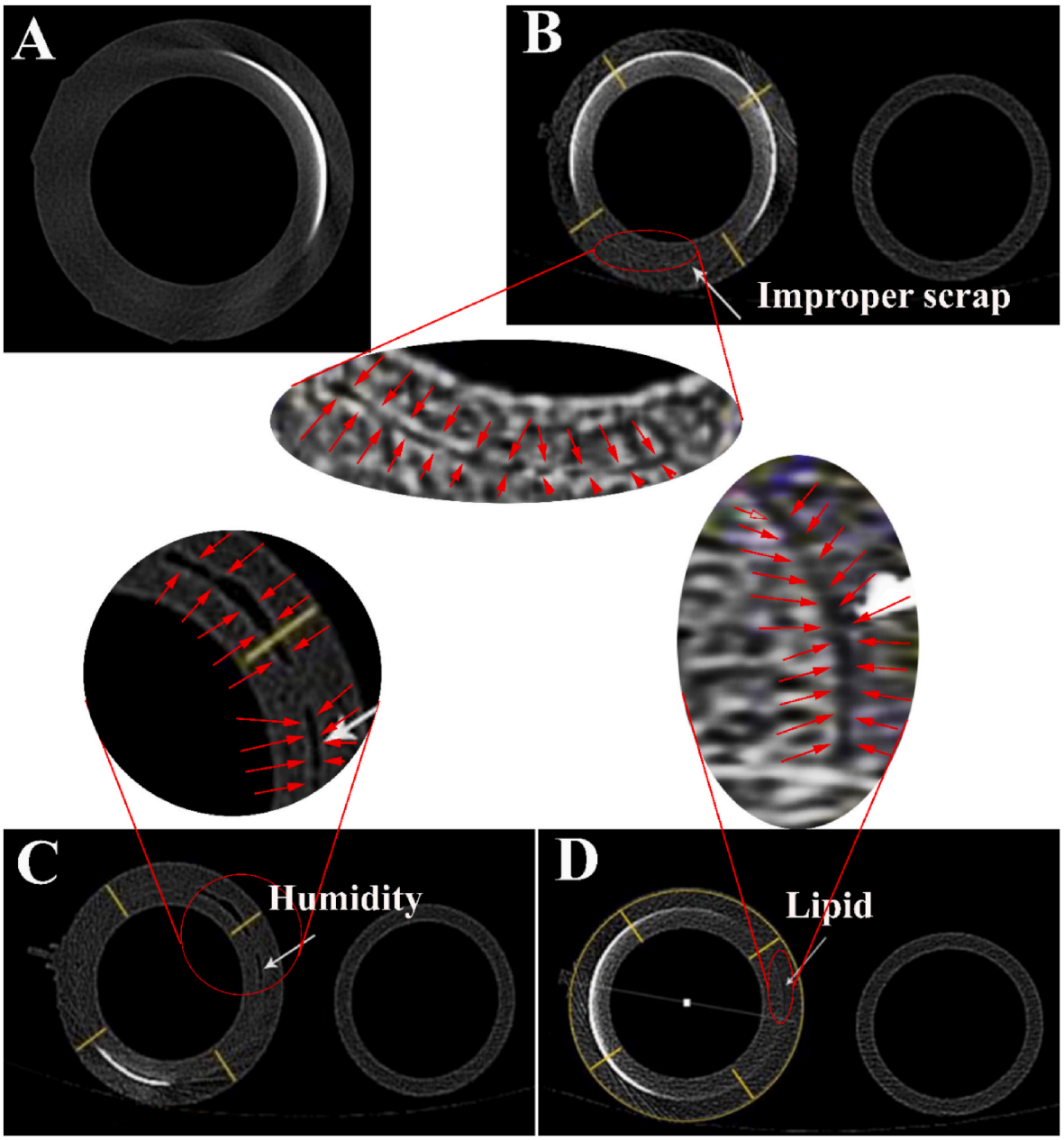

Fig. 7. CT-scans of electrofusion joints (A) without defect, (B) with improper scrap, (C) with trapped humidity, and (D) with a lipid type pollution.

Three types of artificial defects in three different sizes, including improper scraping, lipid pollutants, and moistures in weld zones were created based on the aforementioned procedure. Fig. 5 shows two examples of the prepared defective samples. Indeed, three types of damages, each in three sizes, were investigated. In order to check the repeatability of the results each test was repeated two times. Therefore, in total 27 electrofusion joints were analyzed. Three sizes of artifact defects were 15 mm × 15 mm, 25 mm × 15 mm, and 35 mm × 15 mm. It means all samples with lipids, liquid moistures, and improper-scraping had defects with three sizes at welding surfaces of their pipes before the alignment of the pipe and coupler. Glycerin was used as a lipid pollutant in welding areas. The welding time was set automatically by the welding equipment based on the manufacturer datasheets.

Table 2 indicates heating and cooling time laps of the welding coils. Fig. 6 shows the setup was used in empirical assessments throughout the current study. A crushing de-cohesion test was performed on electrofusion joints containing fabricated defects. The tests were conducted based on the requirements specified in the ISO-13955 standard. According to the engineering best practices, any joint with brittle fracture surface lower than 20% under the crushing de-cohesion test was considered acceptable. Before performing the crushing de-cohesion tests, polyethylene joints were cut alongside the longitudinal axis into two parts, and their interfaces were inspected visually for the presence of any defects.

In addition, the strip-bend test was used to estimate the amount of parent materials fusion. The strip-bend test is an accurate and sensitive

Fig. 8. Shows crushing de-cohesion test on electrofusion joints. Crushing tests showed no considerable differences between appropriately welded and defective joints.

test reflecting the severity of defects in electrofusion joints. According to engineering best practices, a fracture surface of a perfect weld consists only 20% or lower area with brittle fracture evidences after the strip-bend test. In the present study the fracture surfaces of the strip-bend tests were examined using an optical microscope and a scanning electron microscope (SEM).

3. Results and discussion

3.1. FMEA analysis

Table 3 shows the result of FMEA analyses for the damage mechanism identification. Also Table 4 shows the result of mitigation analyses for this piping network. Through Table 4 the appraisal team compared the ideal mitigation actions with available mitigation actions for the PE piping network of present study and the average of their assigned scores is presented as average mitigation coefficient (***M***) in Table 4. Similar comparisons made for survivability and results are provided in Table 5.

Table 6 summaries the risk parameters of the present piping network. The categorization of POFs into five levels from 1 to 5 was done based on Table 7. From Table 6 it can be concluded that three damage mechanisms, including (i) humidity at the welding surfaces, (ii) improper scrapping, and (iii) lipid type pollutants have POF score of 4 and therefore have the highest probability of occurrence. In next steps the COFs were estimated for different damage mechanisms.

As the fluid type, explosion and ignition probability were the same for all damage types, in estimation of COFs for damage types the time and location of the events were considered. Some of imperfections may result in a failure at the joint site in a pressure test and during the construction stage. Therefore, they could be detected in the construction or pre-commissioning phase by doing these investigations. However, some other damage mechanisms may have delayed effects (i.e. not showing a failure during the construction or in the initial operation period) and reduce the strength of the joint without immediate leakage. These last scenario is the worst case and generally its consequences are much dangerous. Consequently, different damage types may have different consequences based on their detection stage in a piping network lifecycle [23–25]. Given the detection phase of the project, each damage type is categorized as A to E consequence levels with E is the highest consequence value. Using Fig. 3 to combine the achieved POF and COF, the risk category of each damage mechanism was obtained and presented in Table 8. As they are shown in italic format in Table 8, three damage types, including humidity at the welding surfaces, improper scrapping, and lipid type pollutants were the most critical damage types with highest risk level (Medium to High). These damage types are selected for further experimental study in next steps.

3.2. Experimental analysis

Fig. 7 shows CT-scans of samples containing man-made defects. The CT-scan was used to trace the fabricated defects at welding areas.

Fig. 8 shows the crushing de-cohesion tests of this study. The crushing de-cohesion tests were performed on electrofusion joints containing man-made defects. Experimental data revealed that test results for all samples, including both appropriately welded and manipulated joints, fall in acceptable ranges in accordance with the Urmia Natural Gas Company's procedure. It can be concluded that these kinds of tests are not sensitive enough to recognize a defective joint from a non-defective joints. Consequently, it was not suitable for the goal of this research and therefore, decided not to continue with this type of tests.

In contrary the strip-bend test has enough sensitivity to discriminate defective joints from appropriately welded joints and used to assess the severity of damage mechanisms in samples. Fig. 9 shows the fractured interface of a sample after the strip-bend test. As it is clear from Fig. 9, some parts of the fractured surfaces are rough, which shows the sign of plastic deformation and is a characteristic of a proper joint and a ductile fracture [26–28]. Additionally, some other parts of the fractured surfaces show smooth areas without any evidence of plastic deformations, which are the characteristics of a brittle fracture [29–31]. Fig. 10 shows the macro-graphs of the fractured surfaces at the defective regions. The fractured surface of the sample with improper scraping (Fig. 10 a) shows an obvious boundary between the scrapped and un-scrapped regions. The scrapped region contains a sign of plastic deformations representative of a well adhesion between the pipe and coupler; however, no signs of plastic deformations observed in the un-scrapped region, implying that the fracture type was brittle and a weak adhesion between the pipe and coupler was occurred. In Fig. 10 (b and c) most areas show evidence of ductile fractures and plastic deformations before the fracture. It means that humidity and lipid type pollutants were not impacted the quality of electrofusion joints, significantly. The fracture surfaces of samples containing humidity and lipid type pollutants for detailed and more accurate investigations were studied using an SEM.

Overall, the fracture surface of samples showed partially characteristics of both the ductile and brittle fractures in different fractions for three studied defect types. Fig. 11 shows the brittle fracture areas of samples related to lipid and moisture pollutants. A fully brittle fracture is obvious from the fractured surface of the sample for lipid type pollutant, while a better adhesion between the pipe and coupler could be concluded from the type of ductile fracture of the sample with trapped moistures. Table 9 summaries the percentages of brittle and ductile fractures for different samples. It can be seen that the proper scraping is more critical for the integrity of the electrofusion joints. For improper scraping, the area percentage of the brittle fracture for all defect sizes were higher than 20%, so considered as unacceptable preparation. Therefore, even leaving a small area without scraping during the electrofusion welding could considerably reduce the strength of the joint. Although, the results of the strip-bend test fall within an acceptable range for all samples with humidity and lipid type defects. The brittle fracture percentages for lipid type pollutants were higher than those of

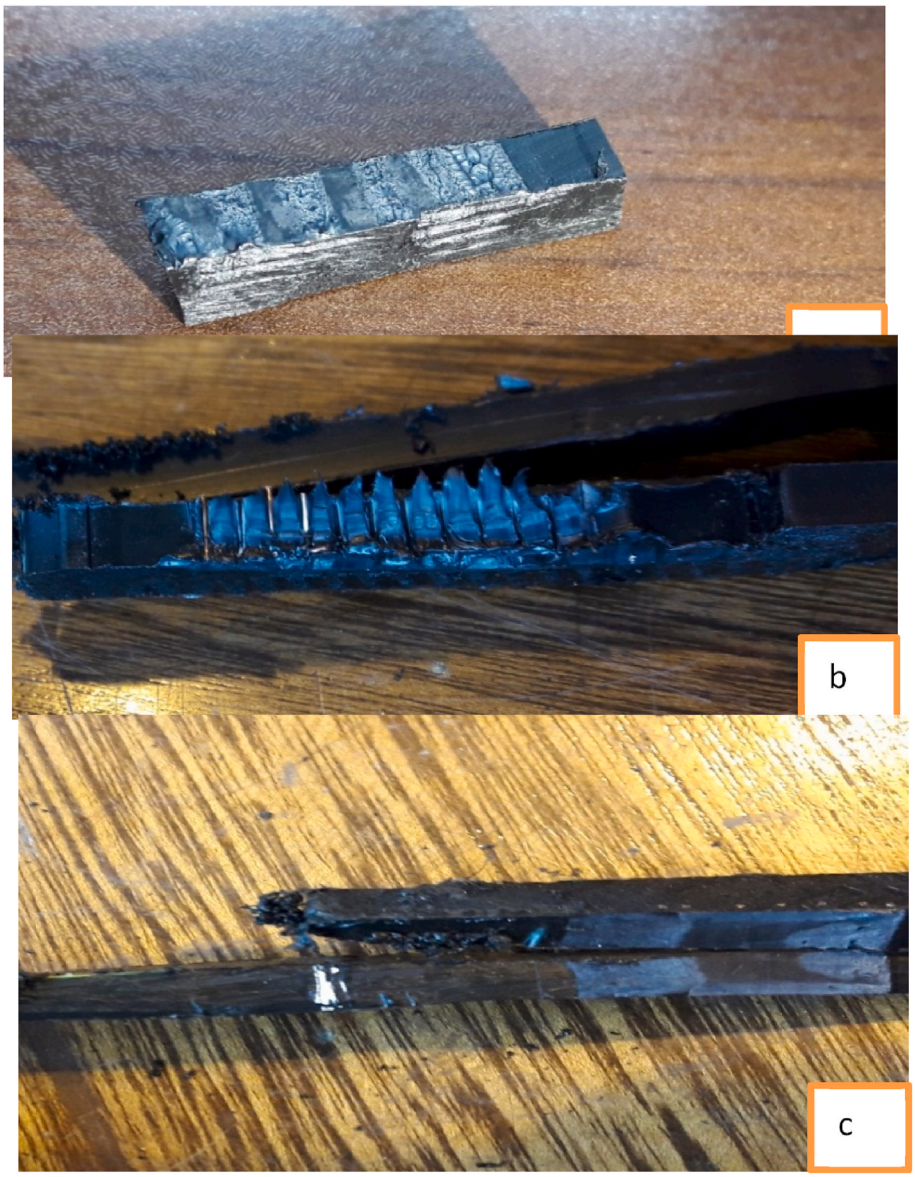

Fig. 9. Optical Macroscopy (× 50) presentation of fractured surface of the electrofusion welding after strip-bend test containing, (a) improper scraping, (b) humidity, (c) lipid type defects.

humidity type pollutants.

4. Conclusion

In this study, FMEA was conducted to identify the root cause of failures in polyethylene natural gas networks of a city in Iran. According to the results, three damage mechanisms in polyethylene networks, including (1) improper scraping, (2) trapped moistures, and (3) incorporation of lipid type pollutants in a welding zone were identified as the most critical failure mechanisms. Empirical assessments were performed to study the severity and share of these damages in welds failure during operation period. The most critical damage mechanism was found to be improper scraping, which followed by lipid type pollutants in the weld zone. The results indicated that, defects caused from trapped moistures in the welding zone compared to other two defects had fewer impacts on the quality of electrofusion joints. This could not be traced using crushing de-cohesion but with strip-bend tests. It is suggested to use stricter quality control measures for the scraping stage of the electrofusion welding to prevent and reduce the number of intermittent failures during the operation period in polyethylene joints.

Author statement

Abolfazl Tutunchi: Conceptualization, Methodology, **Mehdi Eskandarzade**: Data curation, Writing – original draft preparation **Reza Aghamohammadi**: Software, Validation **Tahereh Masalehdan**: Data curation, Visualization **Karim Osouli-Bostanabad**: Writing – original draft preparation.

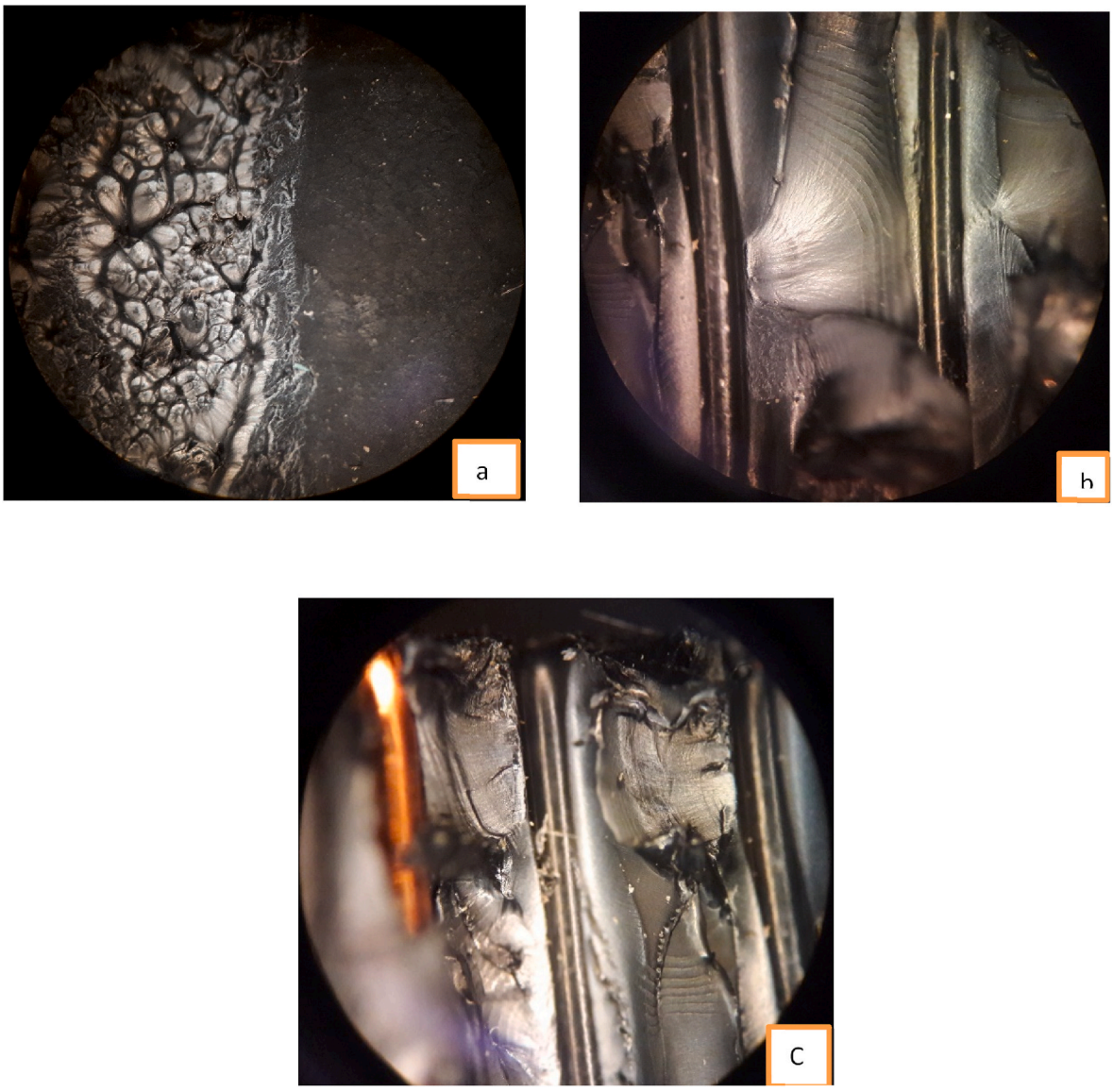

Fig. 10. The microscopic presentation of the fractured surfaces in defective areas of the electrofusion joints after strip-bend tests, (a) Improper scraping (b) Humidity, (c) lipid type defects.

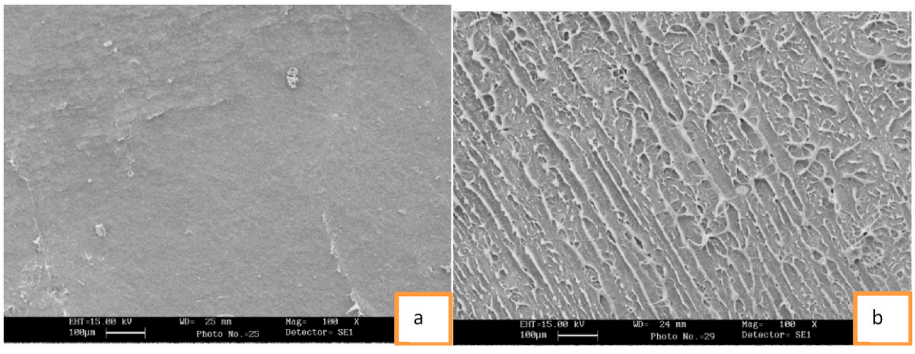

Fig. 11. SEM observation of fractured surfaces with magnification of 100X, (a) Lipid type defect, (b) Humidity type defect.

Table 9
Brittle fracture percentage (L_d) in samples with different defect types and sizes.

Defect type	Defect size	% (L_d)	result
Sound joint	–		The joint is sound and without any defect. Test results are acceptable
Improper scraping	small	20	Strip-bend test is sensitive to this type of defect and share of the brittle fracture increases by increasing the defect size.
	medium	27	
	large	32	
Humidity in the weld zone	small	10	Strip-bend test results for all humidity content samples fall within acceptable range
	medium	14	
	large	18	
Lipid type pollution in the weld zone	small	15	Although that all joints with lipid type defects passed the standard criteria, the brittle fracture percentages were considerable.
	medium	18	
	large	19	

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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