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Review on lifetime predictions of polyethylene pipes: Limitations and trends

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ABSTRACT

Reliable lifetime prediction of underground polyethylene (PE) pipes must be based on a more in-depth understanding of failure mechanisms and a more reliable extrapolation procedure of relatively short test data into long-term service environment. However, there still remain many limitations in the current lifetime prediction methods of PE pipes, such as the deviation of accelerated tests from operating conditions and the empiricism in prediction models. This paper summarizes the failure mechanisms of PE pipes and reviews the researches on lifetime prediction method from two aspects "mechanical" and "chemical" lifetime. A detailed presentation of limitations in current lifetime prediction methods are provided, including failure to consider the material aging and defects or imperfections, crack initiation time, crack tip plasticity and aging, diffusion-limited oxidation and nonlinear Arrhenius behavior. Potential trends of lifetime prediction of PE pipes are further discussed. The chemo-mechanically coupled model and crack layer (CL) model is proposed for the lifetime prediction to reduce the empiricism due to the diffusion-limited oxidation (DLO) or the transition from a continuous SCG to discontinuous.

1. Introduction

As an important pressure-containing structure of lifeline engineering, the plastic pipe occupied a broad market since its gradual application in the 1930s and 1940s [1,2]. PE pipes, as one of the most important members of plastic pipes, have been used for the replacement of metal pipes in lifeline engineering due to its well-known specific properties, such as excellent corrosion resistance, high flexibility, easy maintenance, etc. The market of high density polyethylene (HDPE) pipe is expected to grow at a rate of 5% per year to reach USD 26,518 million by 2025 [3]. Moreover, PE pipes account for more than 90% of the gas pipe network in Europe and 95% of the plastic pipes in the United States [4,5]. At the same time, urban gas pipes are running through densely populated areas all along. Once the failure of PE pipes leads to any leakage or explosion, it will lead to serious consequences. Therefore, studies related to failure and lifetime of PE pipes must be a key concern for material manufacturers and pipe operators.

The stress relaxation and creep behavior of PE related to time and temperature is of great interest to researchers for their importance. The long-term creep rupture curve of PE pipes can be divided into three stages (stage I: ductile failure, stage II: quasi-brittle failure and stage III: brittle failure), as shown in Fig. 1 [6,7]. The lifetime of PE pipes is related to the failure mechanism. In general, the occurrence of ductile failure of PE pipes indicates a short lifetime, but the brittle failure indicates a relatively long lifetime. The threshold of the minimum lifetime for PE pipes is 50 years. The transition from ductile failure to brittle failure always takes a long time, and the "mechanical knee" is difficult to define. In the quasi-brittle stage, the failure of PE pipes is mainly determined by the slow crack growth (SCG), while the brittle failure stage is dominated by the stress-independent material aging. Furthermore, SCG is the main cause of the ultimate failure of the PE application and the sudden failure of polymers-about 15% of failures of all polymer material [8]. In fact, the SCG of PE material is more or less representative of the intrinsic property of the pipe. This property is determined by the raw material mixture ratio and the injection molding process, while being influenced by external variables (stress, temperature and surfactants) and the structural integrity of materials. When PE material is simultaneously subjected to the mechanical stress and exposed to active environments, an acceleration process of the phenomena occurring during SCG can significantly be observed. The generally accepted

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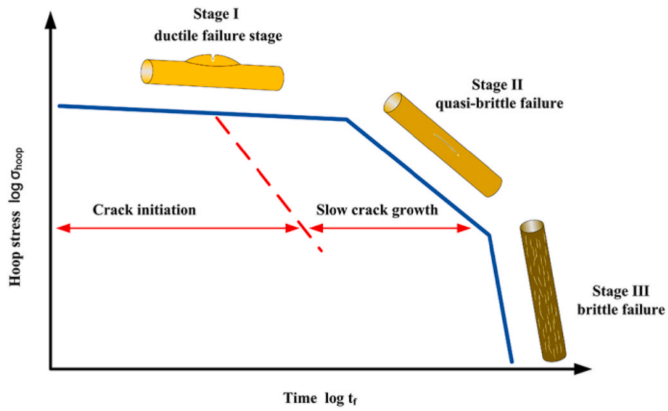

Fig. 1. The long-term creep rupture curve of PE pipes.

mechanism at the basis of this acceleration process, called Environmental Stress Cracking (ESC) [9]. It is believed that the molecular and morphological origins of the resistance of polymeric materials against SCG and ESC are essentially the same [10], and those mechanisms have the similar dependence of damage time on loads and temperatures, as well as the similar brittle damage surface. Therefore, related researches of SCG are usually addressed by using tests based on ESC to reduce the test duration [11–14]. The method of evaluating the lifetime of PE pipes in this way, does not involve the material aging at the molecular level, so it can be considered as a "mechanical" lifetime prediction method. Additionally, the lifetime prediction of PE pipes often takes material aging into account. The relationships between chemical performance and time can be established according to the Arrhenius equation, then a linearized model with respect to the kinetic parameters is applied. The stage III failure region of the long-term creep rupture curve is a result of thermo-oxidative aging and polymer degradation, where the lifetime at this stage can be called "chemical" lifetime [15].

The current lifetime prediction methods consider either creep fracture or material aging singularly. In fact, for PE pipes, it would be conservative to predict the life only considering the aging and degradation of PE materials, because it ignores the non-uniformity of PE pipes' structure, crack growth due to internal defects and the acceleration on material aging of the material by external loading effects [16]. In addition, it is neglected that the material aging itself can be affected by diffusion-limited oxidation as well as non-linear Arrhenius behavior. Besides, the effect of material aging on crack initiation or growth is also unconsidered, and aging leads to changes in the concentration of internal branched chains, which in turn affects the anti-cracking properties. For example, the time for SCG, which is traditionally calculated by Paris-Erdogan relationship, does not take into account not only initiation time of crack, but also not consider the effect of material aging on the crack growth process in PE pipes [17]. Additionally, current methods, such as ESC based methods or hydrostatic testing, can only evaluate the resistance of the new pipe against SCG, but not the residual strength or even lifetime of in-service PE pipes. What's more, for the hydrostatic test, whether the operation of shortening the time of crack growth by increasing the pressure far beyond the actual operating conditions is realistic, remains to be tested [18]. The accelerating effect of thermo-oxidative aging on the cracking process should be considered in PE pipes during the long-term service. Then, there is a new question, how to combine the study of crack growth and material aging for coupled analysis?

In this paper, we summarized failure mechanisms of PE pipes and reviewed the researches on lifetime prediction methods of PE pipes from two aspects-"mechanical" and "chemical" lifetime. Then we summarized some of the problems for the current lifetime prediction methods of PE pipes and highlighted their limitations. After that, we further discussed the trends of lifetime prediction of PE pipes, and provided an outlook on the future development of PE pipes' prediction methods in terms of multi-factor coupling, life cycle prediction and improving accuracy of prediction. Finally, we proposed to use chemo-mechanically coupled models and crack layer (CL) models for the lifetime prediction to reduce the empiricism due to the diffusion-limited oxidation (DLO) or the transition from a continuous SCG to discontinuous.

2. Failure mechanism

The failure of underground PE pipes is a complex process predominated by material aging and stress crack growth, where the outer wall of pipes is subjected to the pressure caused by surrounding soil and the inner wall is subjected to the pressure caused by water distribution or natural gas transmission. Therefore, the failure mechanism of PE pipes is very complex and is not determined by one or two factors alone, but a comprehensive problem involving the material and its integrity, environmental factors and mechanical state [11]. As mentioned earlier, the creep mechanical failure modes of PE pipes can be broadly classified into ductile failure, brittle failure and the transition states between them (quasi-brittle failure) [2,19]. In addition, as a typical polymer, PE pipes are inevitably affected by material aging and degradation caused by the medium [20].

2.1. Ductile failure

At the microscopic level, PE, as a semi-crystalline polymer, has a microstructure consisting of lamellar crystal and amorphous polymer chains. While polymer chains are usually assumed to be folded together in the lamellar crystal [21,22]. In terms of PE materials failure, it is actually the polymer chain connecting both amorphous and crystalline regions-tie molecules that have the greatest impact. The tie molecules, which act as reinforcements, are stretched until they cannot support the applied stress when subjected to the high stress. The lamellar crystal then breaks down into smaller parts, as shown in Fig. 2. In this case, the ductile failure occurs [22].

In macro scale, the ductile failure is characterized by massive yield of material in the vicinity of the damage, and the failure generally occurs at higher stress levels or in shorter time. Macroscopically, this failure mechanism is related to the viscoelastic behavior of PE materials, especially referring to the creep fracture, where the time of ductile failure depends on the creep rate. As shown in Fig. 3, owing to the non-uniformity of the material, a large amount of deformation and local ductile damage occurs at the time of excessive internal pressure applied to PE pipes. Under the action of other large external loads, such as third-party damage, mechanical excavation, etc., ductile failure will also occur [23]. Of course, there may be various other external loads-such as ground settlement, mechanical excavation (as shown in Fig. 4), which generate high stresses that cause ductile failure of the pipe [24–27].

2.2. Brittle failure

Compared to ductile failure, brittle failure of PE materials often occurs under a lower stress level. At the microscopic level, the tie molecules will begin to disentangle and relax over time, some of them are gradually pulled out of the crystalline region. Gradually the stress concentration increases in the small number of remaining tie molecules. When tie molecules are continuously pulled-out and cracks are extended forward, subsequently, the material undergoes brittle fracture. Fig. 5a shows the brittle failure process of PE materials in micro scale [12,22, 28].

In macro scale, the brittle failure is associated with crack growth, and this brittle behavior of SCG takes longer time to occur than the ductile deformation. The failure process is directly related to the craze derive from defects or cavities and the cracks formed by the fracture of fibrils within the craze. Consequently, the cracks leads to the brittle failure when they penetrate the thickness of the pipe [29–32]. It is worth noting

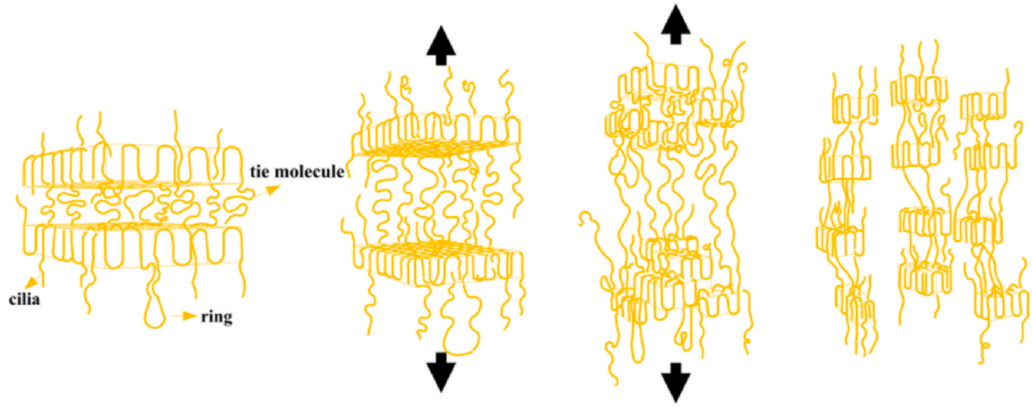

Fig. 2. The ductile failure process of PE at the microscopic level.

Fig. 3. The ductile failure of PE pipe subjected to internal pressure.

Fig. 4. The ductile failure of PE pipe subjected to mechanical excavation [27].

that the breaking of chains is regarded as having a minor contribution to the procedure of the breakdown of fibrils [33]. Fig. 5b shows the typical brittle failure morphology of HDPE pipes. It is well known that minor plastic deformation shown in the figure and long failure time are the characteristics of brittle failure which has a much longer failure time than ductile failure [34,35].

In general, the ductile failure and brittle failure occur simultaneously, and the ultimate failure depends on which process is faster in given conditions of surrounding medium, oxygen, external loads, temperature and defects. For example, when the researchers applied scratches to PE pipes and pressured it to burst, the brittle fracture appeared instead of ductile fracture [36]. Similarly, the brittle fracture was found in the tensile specimen of PE pipes after being added pre-cracks [37].

2.3. Aging failure

Due to the effect of environment, such as thermo-oxidative aging [38], photo-oxidative aging [39], chemical medium [40,41] and biological aging [42], the depletion of antioxidants is accelerated, which leads to the cross-linking, breaking of molecular chains and the failure of PE pipes. For instance, it is generally considered that the reaction of thermo-oxidative aging is a free radical chain reaction with autocatalytic characteristics, including three processes of chain initiation, propagation and termination [43]. At present, the earliest PE pipes in China have been used successfully for more than 40 years, and the usage of them further demonstrate increasing growth. The phenomenon of stress-independent brittle failure appeared only in the laboratory by artificially accelerated aging, as shown in Fig. 6. Obvious heterogeneous aging can be observed, and the aging in the external surface of the pipe is more serious than the internal surface. It is well understood that the more severe thermo-oxidative aging occurs in the external surface of pipe segments exposed to ovens, due to the higher temperature and higher oxygen concentration, and leads to the appearance of chain scission-micro cracks-macro cracks [44]. Moreover, it's noted that the aging on the local crack tip affects the procedure of SCG [17,45].

The ultimate failure state of PE pipes act as a large scale brittle behavior due to material aging. The failure of PE pipes is the result of a combination of ductile failure and brittle failure. In general, the processes above occur simultaneously and the ultimate failure depends on which process is faster under the given material (considering the integrity and defects, etc.), environment parameters and mechanical state. Thus, the failure of PE pipes under the different loading spectrum and environmental conditions can be summarized, as shown in Fig. 7.

3. Lifetime prediction methods

3.1. Mechanical lifetime prediction methods

For the long-term use of PE pipes, the creep behavior, crack initiation and crack including slow and rapid crack growth, have an important influence on the lifetime of PE pipes. The most widely used method for determining the long-term performance and predicting lifetime is formed based on the hydrostatic test of pipe segments [46], and the extrapolation method described in ISO 9080 [47] or ASTM D2837 [48]. For high-quality pipes made of modern thermoplastic materials, it has been proved that the knowledge about SCG of PE pipes is of paramount importance for the lifetime and safety assessment [49–52]. Therefore, Linear elastic fracture mechanics (LEFM) approach has been developed to predict the crack propagation lifetime of PE pipes. But, the resistance against SCG is inherent to the nature of material and is difficult to be

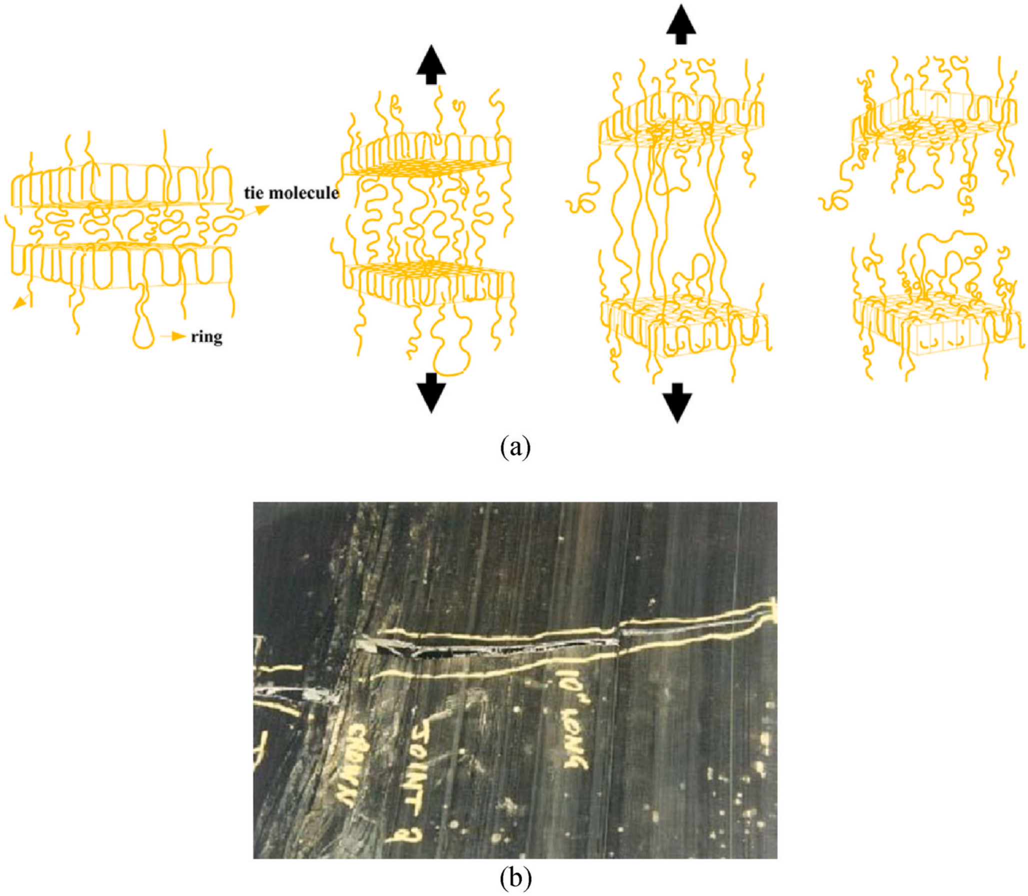

Fig. 5. The brittle failure of PE pipe: (a) microscopic level and (b) macroscopic level [10].

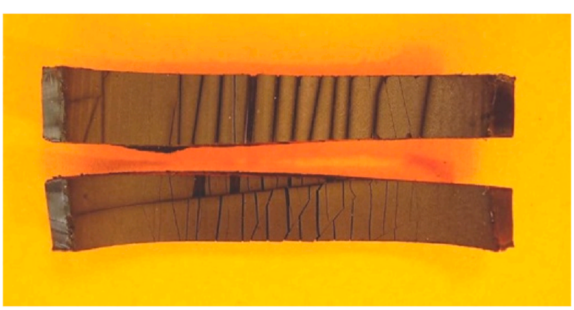

Fig. 6. The aging failure of PE pipe (after aging 25000 h) [44].

tested quickly by experiments. In addition, due to the similar loading, temperature-dependent failure time and fracture surface morphology between the slow crack and the ESC behavior of polymer materials [53], ESC based methods are commonly used to evaluate the resistance against SCG of PE materials [54], such as the notched pipe test [36], the Pennsylvania notch test [55], the full-notch creep test [54], the notched ring test [56,57], the cone test [58] and so on. Owing to the severe test conditions and long test time of the above methods that require not only special defects but also usual usage of surfactants, they are not conducive to actual operation. Therefore, the evaluation methods have been proposed based on the cyclic load test and strain hardening test [59]. All these test methods (listed in Table 1) can be used for quick material ranking and predicting the lifetime durability of PE pipes' materials, but only the method based on cyclic load tests can be used for lifetime prediction. Although surfactant is added to the ESC test, there is no significant chemical reaction during the process and significant dissolution or swelling effect [60]. These methods evaluating the lifetime of PE pipes based on hydrostatic testing, slow crack growth testing and cyclic load testing, do not involve the material aging, so they can be considered as "mechanical" lifetime prediction methods.

(1) Hydrostatic testing

The hydrostatic test uses the standard extrapolation method to predict the long-term lifetime of PE pipes at normal temperature by using the test data at high temperatures and high pressures [61,62]. The method of ISO 9080 extrapolates the service lifetime of PE pipes at the application environment by two or three equations related to the hoop stress, temperature and time to failure. The essence of the method above is the rate process method (RPM) based on Arrhenius equation [63–68].

$$K = A\exp\left(-\frac{E}{RT}\right) \tag{1}$$

where K is the reaction rate. T is the absolute temperature, K. E is the apparent activation energy, J mol^{-1}. A is the frequency factor, d^{-1}. R is the gas constant, 8.31J Kmol^{-1}.

From the above equation, the relationship between temperature (T) and failure time (t) is set as follows.

$$\log(t) = A + \frac{B}{T} \tag{2}$$

Failure time is linearly related to the hoop stress (σ) on the log-log axis, as shown in the following equation.

$$\log(t) = A + B\log\sigma \tag{3}$$

A RPM model is derived by merging Eqs. (2) and (3), while the model

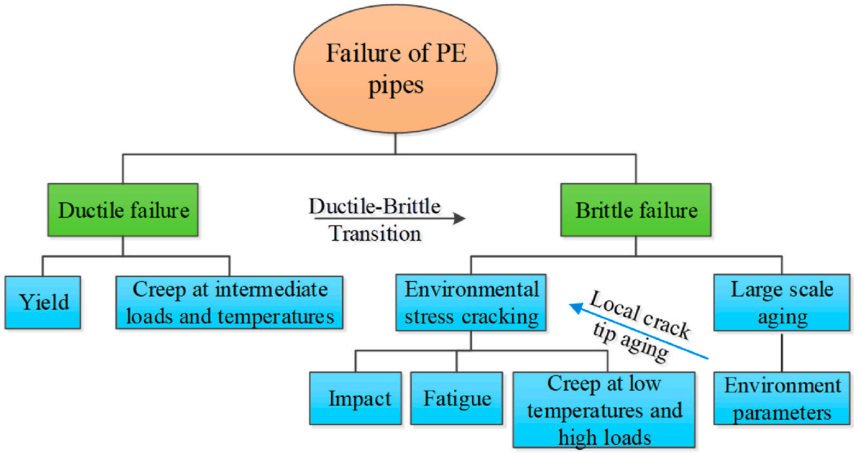

Fig. 7. The failure of PE pipes under the different loading spectrum and environmental conditions [10].

Table 1
Evaluation methods for the resistance against slow crack growth of PE pipes.

Type	Method	Specimen and defect form	Test conditions	Evaluation methods	Related Standards
ESC	Notched pipe test (NPT)	V-shaped grooves around the pipe ring evenly	Hydrostatic test Medium: water Temperature: 80 °C Pressure: 0.8 MPa (PE80) 0.92 MPa (PE100)	PE80: Failure time >165 h PE100: Failure time >500 h	ISO13479
	Pennsylvania notch test (PENT)	Rectangular specimens: 100 mm× 25 mm× 10 mm Prefabricated cracks applied on three sides: main cracks 3.5 mm secondary cracks 1 mm	Tension test Medium: air or water Temperature:80 °C	Crack opening displacement curve Crack initiation time Fracture time Crack growth rate	ISO16241 ASTM F1473
	Full-notch creep test (FNCT)	Rectangular specimens: 110 mm× 10 mm× 10 mm Four side equal depth 1.6 mm prefabricated cracks (razor blade)	Sustained pressure: 4 MPa Temperature: 80 °C Surfactant: Arkopal N100 2%	Cross-section inspection (SEM) Failure time >300 h	ISO16770
	Notched ring test (NRT)	V-shaped notch: 20% wall thickness Prefabricated cracks in the inner wall	Three dots bend test Temperature: 80 °C	Deformation vs time curve	ISO/TS 16479
	Cone test	Complete Pipe Axial notch	Expansion test Axial notch Temperature: 80 °C Surfactant: Arkopal N100 2%	Crack growth rate	ISO 13480
	Notched, Constant Ligament-Stress Test (NCLS)	Strip sample Notch	Sustained stress test Temperature: 50 °C Surfactant	Failure time	ASTM F2136
	Stripe bending test	Strip sample Indentation	Surfactant: Igepal 10%	Failure time >1000 h	ASTM D1693
Cyclic load test	Fatigue crack growth experiment	Cracked round bar Circumferential prefabricated cracks	Fatigue loading 10Hz sine wave loading	Stress range vs total number of cycles curve	ISO 18489
Tension test	Strain hardening test (SH)	Dumbbell specimen: 0.3–1.0 mm	Tension test Temperature: 80 °C	Tensile ratio vs stress curve Strain hardening modulus	ISO 18488

of ISO 9080 differs from ASTM D2837. A three-parameter model is used in the ASTM D2837, but a four-parameter model used in the ISO 9080.

$$\text{Three}-\text{parameter model:}\ \log(t)=A+\frac{B}{T}+\frac{C\log\sigma}{T} \tag{4}$$

$$\text{Four}-\text{parameter model:}\ \log(t)=A+\frac{B}{T}+C\log\sigma+\frac{D\log\sigma}{T} \tag{5}$$

where A, B, C and D are constants. t is the failure time, h. σ is the hoop stress, Pa. T is absolute temperature, K.

Statistical methods are commonly used to deal with the discreteness of long-term hydrostatic test data. For example, ISO 9080 considers that the failure time of different samples varies widely under the same temperature and stress level, but $\log_{10}t$ follows the normal distribution. Under the circumstances (e.g. the same T and σ) a certain lower confidence limit α determines the corresponding failure time t.

$$\log_{10}t=A+\frac{B}{T}+C\log\sigma+\frac{D\log\sigma}{T}+e \tag{6}$$

where, e is the error variable, which follows the normal distribution. The four parameters above can be obtained by the multiple regression analysis based on extensive experimental data. Hydrostatic strength is defined as a hoop stress of pipe when the lower confidence limit equals to 0.975. Generally, the hydrostatic design basis (HDB) and the minimum required strength (MRS) are used to obtain the allowable range of rated pressure influenced by the pipe diameter, thickness and safety factor. Currently, the minimum design lifetime of PE pipes is required to be 50 years [69].

(2) Slow crack growth testing

Many researchers have used the method of LEFM to study and characterize the resistance against SCG of polymeric materials for pipes [70,71]. Similar to the testing of metals, the compact tension (CT) specimens of PE pipes (e.g. Fig. 8a) were also tested subjected to constant tension to obtain the rule of crack length a with time t [50]. Advances in computational power have enabled the possibility of applying simulation to the failure of polymer applications, such as some finite element models were established (Fig. 8b) to analyze the crack growth behavior of pre-cracked PE pipes subjected to internal pressure and external loadings [72,73]. A typical curve of crack length versus time is shown in Fig. 8c. It can be seen from the changing slope of the curve that the speed of crack growth is accelerating. When the critical crack length a_c is reached, the crack growth becomes unstable and the specimen finally ruptures.

When the plastic deformation is confined only near the leading edge of the crack, LEFM is usually valid. Therefore, LEFM can be used to describe the stress field near the crack tip, as demonstrated in the relevant literature [74,75]. According to the LEFM principle, the crack growth rate under static loading is determined by the applied stress intensity factor K_I, in accordance with the following Paris-Erdogan formula [76,77].

$$\frac{da}{dt} = A(K_I)^m \tag{7}$$

$$K_I = \sigma \cdot \sqrt{a} \cdot Y \tag{8}$$

where A and m are constants that depend on the material, as well as on the testing variables such as temperature and environment. a is the crack length. σ is the applied stress, and Y is the shape factor. However, this relationship usually holds only in the intermediate range of the curve of crack growth. There is a deviation between the power law and the curve, as shown the area III in Fig. 8d. When K_I approaches the threshold K_{Ith}, the crack growth rate da/dt in the area I, decreases rapidly to a very small value, while in the area III the crack growth rate increases significantly with the increasing of K_I. When stress intensity factor tends to the fracture toughness K_{IC} of the material, the crack growth becomes unstable. At the initial stage of creep crack growth, the initial time follows a power law.

$$t_{in} = B \cdot K_I^{-n} \tag{9}$$

According to the results of experiment, Stern [70] indicated B and n in Eq. (9) are constants depended on the materials and testing conditions. Generally, in view of a pipe containing cracks or defects, the total failure time t_L is the sum of the time for crack initiation t_{in} and the time for SCG t_{scg} in which the crack growth is relatively slow. Visually, the failure occurs when the initial crack a_0 expands to the critical crack size

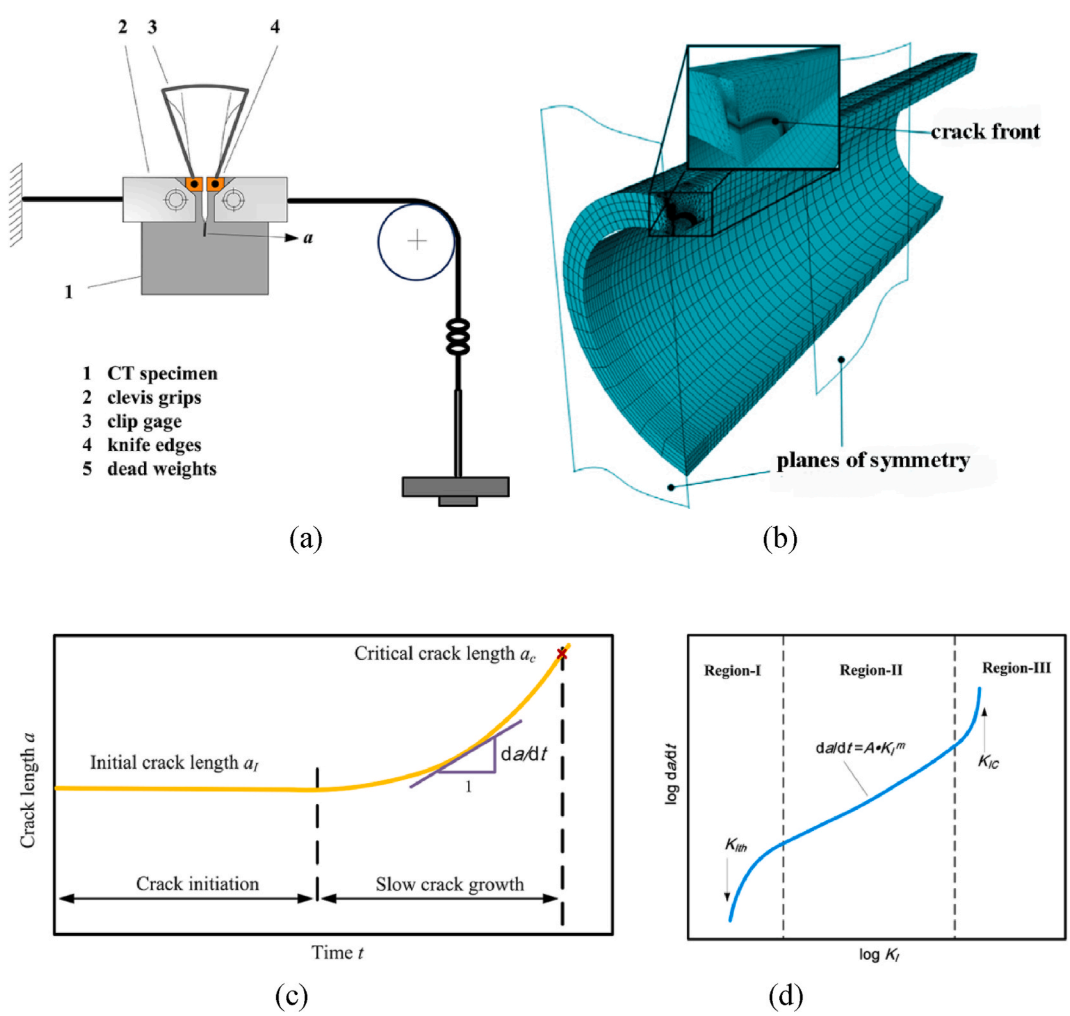

Fig. 8. (a) Testing and loading device for compact tension (CT) specimens with notches [50], (b) the finite element model of PE pipe with initial crack [72], (c) variation curve of typical crack length with loading time [50], and (d) crack growth rate as a function of applied stress intensity factor [50].

a_c. The t_{scg} can be obtained by integrating Eq. (7), so the total lifetime of the pipe is described in Eq. (10). Although the method of LEFM has been used to predict the pipe lifetime frequently [29,78], there is still a lack of experimental proof where a direct quantitative correlation exists between the failure time predicted by LEFM and the actual lifetime of the pipe [50].

$$t_L = t_{in} + t_{scg} = B \cdot K_I^{-n} + \int_{a_0}^{s} \frac{da}{A\left[K_I\left(\sigma_{hoop}, a\right)\right]^m} \tag{10}$$

where σ_{hoop} is the hoop stress of pipe. a_0 is the initial crack length. s is the wall thickness of the pipe.

(3) Cyclic load testing

Currently, methods have been implemented using the cyclic load test for cracked round bar (CRB) specimens or dumbbell specimens to characterize crack growth resistance and evaluate the service lifetime of PE specimens [79], but the method based on CRB is more widely studied and used. Different studies have indicated that the crack growth behavior in cyclic load tests and uniaxial static creep tests are often caused by the same failure mechanism within the boundary range of LEFM [80,81]. Moreover, these studies also confirmed that for different grades of PE pipe materials, the results of cyclic load tests are in good agreement with the results of hydrostatic tests [82]. In order to extrapolate the static failure behavior according to cyclic load tests, Lang and Pinter proposed a concept of extrapolation- Crack Kinetic Extrapolation Concept which combines the advantages of the cyclic CRB test with modern concepts of LEFM [83,84]. In this method, loadings have been applied to the specimen by controlling the loading ratio R which is the ratio of the minimum load to the maximum load in one loading cycle, as shown in Eq. (11). Then, the driving force-stress intensity factor K_I of SCG in static testing is replaced by the difference between the maximum and minimum stress intensity factors ΔK_I in the fatigue test in Eq. (12).

$$R = \frac{F_{min}}{F_{max}} = \frac{K_{I,min}}{K_{I,max}} \tag{11}$$

$$\Delta K_I = K_{I,max} - K_{I,min} = K_{I,max} \cdot (1 - R) \tag{12}$$

In the cyclic load testing, the time of crack initiation and SCG is influenced by the frequency f. Therefore, the crack growth rate is defined as the change in the crack length per cycle N (Eq. (13)). However, the material parameters A and m in Paris-Erdogan formula stay the same in any stress ratio R. In order to create connection between the kinetics of fatigue crack growth and static loading, the fatigue crack growth rate is multiplied by the frequency f to obtain the crack growth rate per unit time [85,86] (Eq. (14)).

$$\frac{da}{dN} = A(K_I)^m \tag{13}$$

$$\frac{da}{dt} = \frac{da}{dN} \cdot f \tag{14}$$

This extrapolation method determines the fatigue creep curve of PE pipe's material at the application temperature near 23 °C [84]. The static load condition is achieved by varying the cyclic test parameters as shown in Fig. 9, and the corresponding extrapolation steps are shown in Fig. 10, where the detail process can be found in Ref. [81].

The cyclic CRB testing has been successfully applied to predict the fracture mechanics lifetime of pressurized PE pipes [87,88]. What's more, Hutař et al. [89] have also investigated the effect of residual stress on lifetime of PE pipes. Laiarinandrasana et al. [90] conducted slow crack growth experiments on PE pipes by using tensile tests of pipe ring and CRB experiments, respectively, and compared the results with long-term hydrostatic test. The experimental results showed that the rule of the slow crack growth can be better predicted by using the above two experiments. Kratochvilla et al. [91] selected nine different kinds of PE100 and PE100-RC pipes and used different methods to evaluate the resistance against SCG of materials, such as the CRB method, notched pipe test, double notch creep test and Charpy impact test. Meanwhile, some significant explorations have also been made by related scholars to predict the lifetime of PE pipes in-service conditions by using the fatigue lifetime prediction method [92]. Consequently, the concept of extrapolation method based on short-term fatigue tests of CRB specimens, provides a valuable and effective tool for lifetime assessment of thermoplastic pipes (e.g. PE pipe) [93].

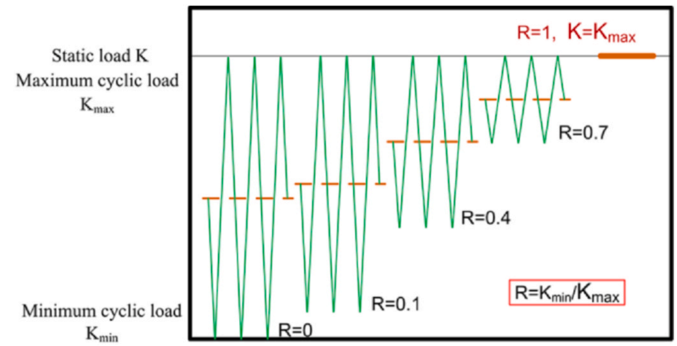

Fig. 9. Relationship between different stress intensity factors K_I and stress ratio R [83].

3.2. Chemical lifetime prediction methods

Due to the influence of the ambient conditions, the performance of polymers or their products will gradually deteriorate during the use or storage. According to standard mechanistic scheme in oxidation, the polymer undergoes six sets of closed-loop chain reactions in which the alkyl radical or peroxy radical plays a key role [94]. Thus, the chemical lifetime of PE material is closely related to free radicals, and the following relationship exists among the stability of materials, the material aging or degradation, and free radicals, as shown in Fig. 11. Actually, the time between the stability and the aging failure of this material represents its chemical lifetime. By inhibiting the formation and propagation of free radicals, the performance of the material in the environment can be guaranteed for a long time and the life can be improved. By adding antioxidants in PE pipes, the further growth of radical in PE is prevented or the termination process of the free radical chain reaction is advanced. Conversely, promoting the formation and propagation of free radicals can accelerate the decomposition of material and shorten the service lifetime. Some studies have shown that controllable degradability of the polymer has been achieved in laboratory [95]. For instance, researchers added some "mechanophore" to the polymer and activate the radical by some excitation methods (internal esterification, etc.), thus achieved the controllable degradability of polymer [96]. In addition, the aging of buried gas PE pipes is mainly subjected to thermo-oxidative aging. The process consists of the transfer or consumption of the antioxidant and the degradation of the PE matrix. In order to facilitate the lifetime prediction of the in-service pipe, the relationship between microscopic behavior and macroscopic performance of aged PE need to be established.

(1) Impact of antioxidants

The lifetime prediction of polymer is closely related to the behavior of consumption and diffusion of antioxidants. The tests and aging studies for polymer have focused on the effectiveness of antioxidants or their combinations [97,98]. This is followed by the question of effectiveness under high temperature or similar exposure conditions in short-term use [99–102]. In terms of PE pipes, it is of significant to discuss the diffusion

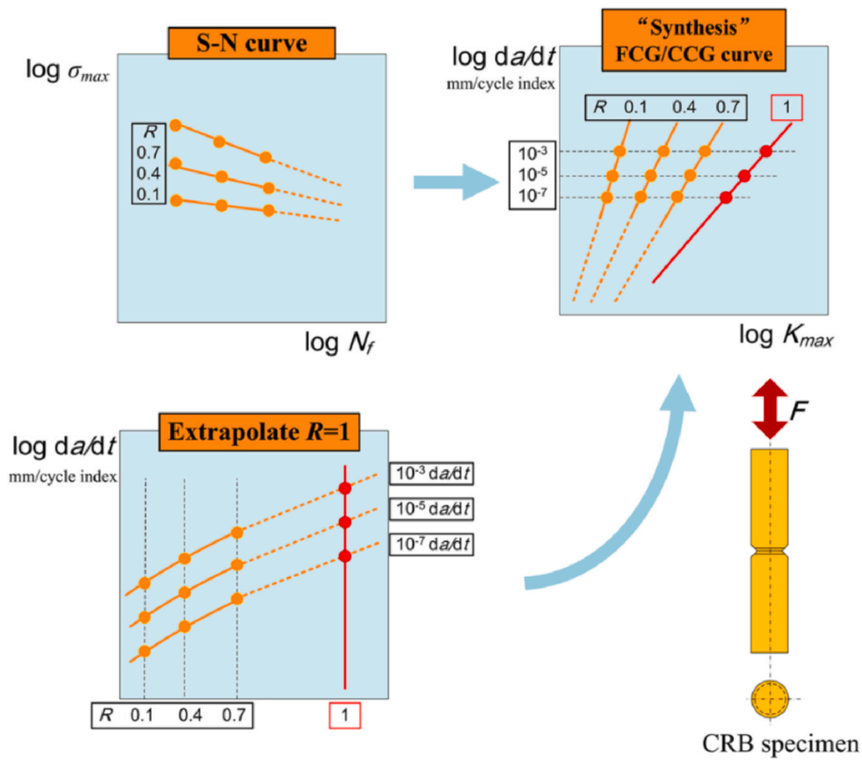

Fig. 10. Procedure to generate synthetic crack growth curves for static loading ($R = 1$) based on cyclic CRB tests [81].

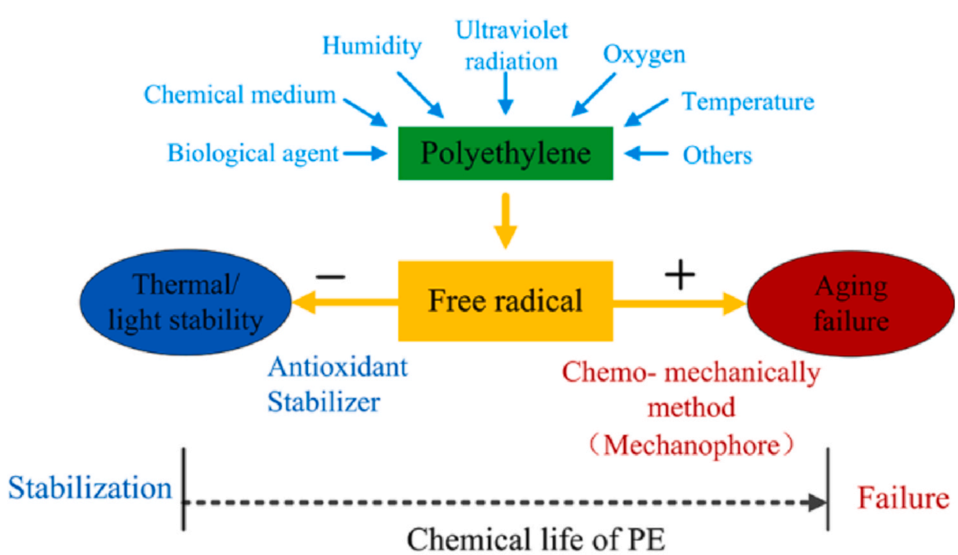

Fig. 11. The relationship between chemical lifetime of PE and the environment.

and consumption of antioxidants in pipe wall due to thermo-oxidative aging [103–105]. Another special field of significant practical importance is the effect of chlorinated species on PE pipe failure; what happens is that the chlorinated species causes early loss of antioxidant stability which in turn opens the door for thermo-oxidation [106–109]. Currently thermal analysis methods are commonly used to determine the consumption of antioxidants such as differential scanning calorimetry (DSC) and high performance liquid chromatography (HPLC). It is necessary to measure the time or temperature at which the autocatalytic oxidation reaction occurs under high temperature and enriched oxygen, i.e., the oxidation induction time (OIT) or oxidation offset temperature (OOT) [110]. Absolutely, OIT is widely used for the determination of the thermo-oxidative resistance of PE materials [111], and can be used to approximately estimate of the lifetime of polymeric materials due to its existed linear relationship with the concentration of phenolic antioxidant [112]. Some researchers have developed lifetime prediction models based on Arrhenius equation for PE water pipes subjected to hydrostatic testing [113] and PE gas pipes subjected to thermo-oxidative aging [14, 114], respectively, where OIT of the PE material is the most important indicator.

The life prediction based on hydrostatic testing [113]

$$\ln(\text{OIT}) = S_T \times t + \ln(\text{OIT}_0) \quad (15)$$

$$\ln(S_T) = -\frac{E_a}{R} \times \frac{1}{T} + \ln C \tag{16}$$

where T is absolute temperature. t is exposure time. S_T is the rate of depletion of antioxidants (reaction rate). OIT_0 is the initial OIT value for the unexposed PE pipe. E_a is the activation energy of the reaction (depletion of antioxidants), KJ mol^{-1}. R is the gas constant, 8.31J $Kmol^{-1}$. C is a constant independent of test temperature.

The life prediction based on thermo-oxidative aging [114]

$$\ln(P) = -K \times t + \ln(B) \tag{17}$$

$$\ln(K) = \ln A - \frac{E}{R} \times \frac{1}{T} \tag{18}$$

where P is the ratio of properties before and after aging. B is the initial value of the property. t is the exposure time. Equation 18 is the logarithm form of equation1.

The results of the above methods for the lifetime prediction are achieved more than 50 years at the room temperature. However, it should be noted that the test must be carried out at a temperature not too far from the expected temperature of the actual application [115]. The performance decay process of aging PE pipes can take place at different distances from the pipe surface and is affected by oxygen diffusion [116]. Despite the addition of antioxidants, thermal oxidative degradation continues. Studies have shown that PE pipes degrade significantly even in the existence of high levels of antioxidants [117], or when OIT data indicate that the material is sufficiently stable [118].

(2) Oxidation of PE

When the antioxidant is consumed, the PE material degrades rapidly. Similarly, a lifetime prediction equation based on hydroperoxides was established [113].

$$\ln(\mathrm{ROOH}) = S_T \times t + \ln(\mathrm{ROOH}_0) \tag{19}$$

$$\ln(S_T) = -\frac{E_a}{R} \times \frac{1}{T} + \ln C \tag{20}$$

where ROOH is the hydroperoxide oxidative products (ROOH) value for the pipe exposed at test temperature T and exposure time t. S_T is the rate of formation of ROOH (reaction rate). $ROOH_0$ is the initial ROOH value for the unexposed PE pipe.

Depletion of antioxidants of PE100 water pipes exposed to water and subjected to hydrostatic pressure at a relatively low temperature (up to 80 °C) was monitored by using the DSC testing and initiation of thermo-oxidative degradation was assessed by iodometric detection of hydroperoxides [113]. Meanwhile, an empirical model based on Arrhenius was developed, similar to Eq. (15) and Eq. (19), to extrapolate the lifetime of PE100 pipe at different operating temperatures (10–25 °C). In addition, a good agreement between the predicted results by this way and the experimental results in low temperature illustrates the correctness of the empirical model. Therefore, the combination of pressure testing and chemical composition analysis will be a very powerful tool for predicting the lifetime of plastic pipes [118].

(3) Relationship between material degradation and mechanical properties

The purpose of accelerated aging of PE pipes indoors is to accelerate the chemical process of their degradation. The degradation of PE pipes is usually characterized by some chemical or physical methods, such as IR detection, color change, cross-linking behavior, molecular weight analysis, melting behavior or morphological characterization [119]. However, these methods are not applicable to the inspection of actual pipes more or less. Therefore, in order to evaluate the lifetime of in-service pipes, it was necessary to establish the relationship between the microscopic mechanism of aging and the macroscopic physical properties. Aging at the micro scale are also usually monitored by tensile elongation rate, modulus analysis, fracture analysis or similar mechanical tests. For example, some researchers have used the maximum tensile force [120], the modulus of elasticity [121] of PE pipe materials to characterize the decay of their properties and combined them with the Arrhenius equation to predict the lifetime. Further, the aging degree of PE pipes suffering from thermo-oxidation, has also been detected by the elastic modulus [122], glass transition temperature [123], failure strain [124], local embrittlement [125] and some other properties [126]. In addition, some molecular dynamics simulations are used to analyze the effects of the microstructure of PE on macroscopic properties [127,128].

4. Limitations in lifetime prediction methods

4.1. Limitations in mechanical lifetime prediction methods

4.1.1. Limitations of lifetime prediction based on hydrostatic test

Long-term hydrostatic test shortened the test time by increasing the hoop stress, but led to a ductile-brittle transition of PE pipes, which created a deviation from the actual failure mechanism of pipe-a long-term brittle failure subjected to the low pressure. In addition, the test temperature must be less than the melting temperature [18,49], consequently, cannot be increased indefinitely, because it is limited by the melting or softening of the material. Moreover, owing to the lack of consideration for the effect of material aging and defects on the long-term performance of PE pipes [49], there would be more significant deviations between the results in hydrostatic tests and the operating conditions.

(1) Ignoring material aging

Based on the rate process theory, ISO 9080 or ASTM D2837 describes the failure of plastics using the Eyring equation at the micro level or the Arrhenius equation at the macro level [129,130]. The lifetime prediction method in this standard assumes the micro-mechanism of each failure region in the creep failure curve (see Fig. 1) is controlled solely by the rate process theory. However, the simple rate process theory controlled by a single microscopic failure mechanism can be complicated by the presence of temperature differences or aging, or any structural changes in the material. It is why this standard specifically emphasizes that aging effects of materials are not considered [61]. However, material aging is inevitable in PE pipes during actual operation. Even in the hydrostatic test, there will be aging products in PE pipe after a long time heating and pressurization which had been used to evaluate the lifetime of PE pipes [113]. Related studies have also shown that there are many different micro-mechanisms that may lead to the failure of PE, including adsorption and diffusion of oxygen or other chemical substances in the material, diffusion and desorption of antioxidants from the material into the exposure conditions and various degradation reactions involving antioxidants and polymers [129,131]. Actually, the experimental results based on the method in ISO 9080 or ASTM D2837 seem to be a promising match for the failure of PE pipes in service, but must be based on the premise that many aging micro-mechanisms may occur simultaneously and the rate dependent kinetic processes with different temperature may be involved.

(2) Ignoring defects or imperfections

Defects or imperfections have a great impact on the long-term performance of PE pipes. In practical applications, the damage caused by uncontrollable factors in the pipe transportation, installation and the operation process is unavoidable, such as scratches, impacts, pipe ruptures and non-uniform loads. Deviations in the pipe manufacturing process can also lead to some degree of pipe pre-damage. Usually, these factors increase the possibility of crack initiation in the PE pipe at the defects. When performing the pipeline design, the effects of defects are usually avoided by introducing an appropriate design or safety factor based on the experience. However, it is not only difficult to assess the impact of these defects or combinations thereof on proper safety factor for new material systems, but also to determine meaningful safety factors of existing pipe materials with combinations of defects in the worst-case scenario [49]. The failure mechanism in hydrostatic testing should be studied more clearly, rather than eliminate errors by using empirical safety factors or using a statistical method.

(3) Ignoring discontinuous SCG

The existing standards (ISO 9080, ASTM D2837) offered tests at elevated temperatures (80 °C and 60 °C) and extrapolation to the ambient temperatures, i.e., empirical method, to solve the problem that the brittle failure at ambient temperature takes too long time. However, acceleration of testing for lifetime by elevated temperature or load level might cause the changes in mechanism and kinetics of SCG, where a transition from continuous SCG to discontinuous might occur. For example, the discontinuous SCG mode have been found in PE pipes subjected to evaluated temperature, fatigue or creep conditions [132,133]. This transition might make it invalid to predict lifetime of PE pipes based on hydrostatic tests, since such extrapolation in this method crosses the boundary between discontinuous and continuous SCG [132].

(4) Others

The current hydrostatic tests have become increasingly inadequate to meet the demands of rapidly increasing material properties. Generally, the lifetime prediction based on hydrostatic test requires about 1 year of test time, and longer test period is needed with the improvement of PE material. Therefore, there is a need to find new alternatives or improved test protocols based on a good agreement between test results and long-term operational results in ambient environments. Even so, the lifetime of in-service pipes cannot be predicted based on the extrapolation method of hydrostatic tests, so as the remaining lifetime of pipes.

4.1.2. Limitations of lifetime prediction based on LEFM

(1) Ignoring crack initiation time

The lack of information on the size, shape and location of the initial crack (generally micro-crack) in PE pipes leads to great uncertainty in crack initiation and growth. For example, the crack initiation time does depend heavily on the geometry of the initial crack, and the results of crack growth are different for the notch caused by a razor blade or a fatigue pre-crack. However, all the current crack growth tests are performed by artificially prefabricated initial cracks on specimens or pipes to study their SCG behavior under a given loading environment [37,71]. For the initial crack growth stage (region I in Fig. 8c), the current lifetime prediction model is established based on Paris-Erdogan relationship between the creep crack growth rate and stress intensity factor K_I. Therefore, transient effects that usually appear in the initial stage of the crack growth or short crack effects and creep crack growth in the region I (Fig. 8c) are neglected [49]. In addition, the material aging is unconsidered for the analysis of defects, which results that the crack initiation time cannot be predicted. In fact, the initiation of the crack usually contributes a significant part to the total failure [17] and is the key to predict the lifetime of PE pipes.

(2) Ignoring crack tip plasticity and aging

Under the internal pressure and external loads, the stress effected on defects in PE pipes is usually in the non-linear viscoelastic range. Depending on the degree of non-linearity, the associated effects may be significant or negligible [49]. Thus, the applicability of the linear elasticity theory must be further considered to ensure the predicting results of PE pipes close to the operating conditions. Recently, increasing researches indicated that, considering that a large amount of plasticity is generally observed in the immediate vicinity of a crack tip-crack tip plasticity, applying only LEFM parameters such as the stress intensity factor is fundamentally inappropriate [52]. Especially, with the reformation of technology, the latest generation of PE pipe materials tends to have better crack tip plasticity.

In addition, the effect of material aging on the crack growth process is not yet clear. Preliminary experiments on MDPE and HDPE pipe segments showed that the effect of material aging was significantly enhanced near the crack, i.e., local crack tip aging, compared to the remaining pipe segments [129,134]. Material aging causes changes in molecular mass, the concentration and length of short branched chains [85,135], which affects the SCG behavior. Furthermore, the existence of stabilizer will obviously affect crack tip aging processes [45], which brings challenges to the lifetime prediction method based on LEFM. Therefore, the current evaluation methods are established based on the evaluation of the SCG resistance of new pipes, such as cyclic load tests using CRB specimens. Even though there is proof in the literature that the result of cyclic load test agrees with it in hydrostatic test, the applicability for actual underground PE pipes remains to be examined. Accordingly, these methods based on LEFM cannot predict the lifetime or remaining lifetime of in-service pipes in a nondestructive way, instead of being limited to the lab, which is the pipeline operators are more concerned about.

4.2. Limitations in chemical lifetime prediction methods

(1) Ignoring complex aging mechanism

For the prediction of chemical life of PE pipes, there are many complications that lead to the difficulty of prediction. The first one is about the correlation between the antioxidant depletion and matrix aging. Relevant studies have shown that there is no clear time demarcation between antioxidant depletion and material aging degradation, and the two processes often occur simultaneously [113,136]. However, only when the antioxidant is completely consumed and the hydroperoxide in PE pipes reaches a critical value, the physical properties of the pipes will be significantly reduced [113]. This is due to the fact that there will be stabilizers to play a positive role in inhibiting the thermal degradation of the PE matrix after the antioxidant is consumed, which is the effective thermal stabilizing effect for a long time at low temperature [137–139]. The reason for the discussion on the correlation between the two processes is that the degradation of PE pipes currently does not reach a point where there is a significant reduction in the physical properties of PE pipes. PE pipes in hydrostatic tests have always produced hydroperoxides, and the relationship between their concentration and apparent performance degradation (such as "mechanical knee") is unclear. For example, a further research is needed on whether the inflection point at which hydroperoxides show a sharp rise is the "mechanical knee" described in the long-term creep curve.

In addition, although the antioxidant is proved to have a significant improvement for the resistance to material aging, it has been found that partial loss of mechanical properties and oxidative degradation can also be observed at lower temperatures, and that there is a large amount of free antioxidant in the material at this time [140]. Thus, the effect of antioxidants seems to be limited, and the degradation reaction cannot be stopped completely, which possibly because only part antioxidants work in the degradation inhibition process. In a word, antioxidant depletion and thermal degradation process of the matrix affect the lifetime of PE pipes in any case. But the current use of OIT or ROOH alone to predict the lifetime is too conservative and clearly does not match the microscopic aging process. Moreover, there is a lack of research on whether the above two processes (antioxidant depletion process and thermal decomposition process) can be affected by changes of the force field which origins from defects or external loads.

(2) Ignoring diffusion-limited oxidation

Diffusion-limited oxidation (DLO) affects the thermal degradation process of PE pipes, which reflects the relative relationship between the supply and consumption of oxygen [141,142]. DLO is at the core of the unresolved conflict between degradation complexity and the knowledge in the polymer aging, is a key factor in the difference between accelerated thermo-oxidative aging and actual aging behavior under service conditions [143], and is also the reason for the incorporation of more engineering-based test methods in many lifetime predictions. DLO is affected by many factors, such as the geometry of the material, the rate of oxygen depletion, oxygen permeability coefficient and the partial pressure of oxygen of the surrounding environment [144]. The current lifetime prediction method based on hydrostatic testing uses Arrhenius extrapolation to predict lifetime through limited temperature and number of data points. However, the inhomogeneous degradation process of the material is ignored in this approach, which can also not accommodate mechanical changes and non-linear temperature change.

As shown in Fig. 12, inhomogeneous degradation was observed in cross-linked polyethylene and cross-linked ethylene propylene rubber films at different temperatures [145]. It is deterministic that DLO leads to the inhomogeneous degradation of the polymer specimen from the surface to the core [146]. What's more, this degraded surface layer of polymer is often manifested in reduction of molecular weight and material toughness. For Polybutylene (PB), the decreased molecular weight always leads to increase of crystallinity and density [132]. The densification of surface layer results in buildup of tensile residual stress which causes the cracks initiation combining with decreasing toughness, as shown in Fig. 13.

Unfortunately, there is a lack of research reports on the DLO or multiple cracks initiation of PE pipes under thermo-oxidation aging, also the variability of surface and bulk degradation of PE pipes. For the lifetime prediction of PE pipes, material aging is generally considered as a homogeneous aging process. Even if the difference between the inside and outside of the material is considered, the reason of the difference is only briefly discussed without discussing the correlation between them or their effects on the lifetime [114,121].

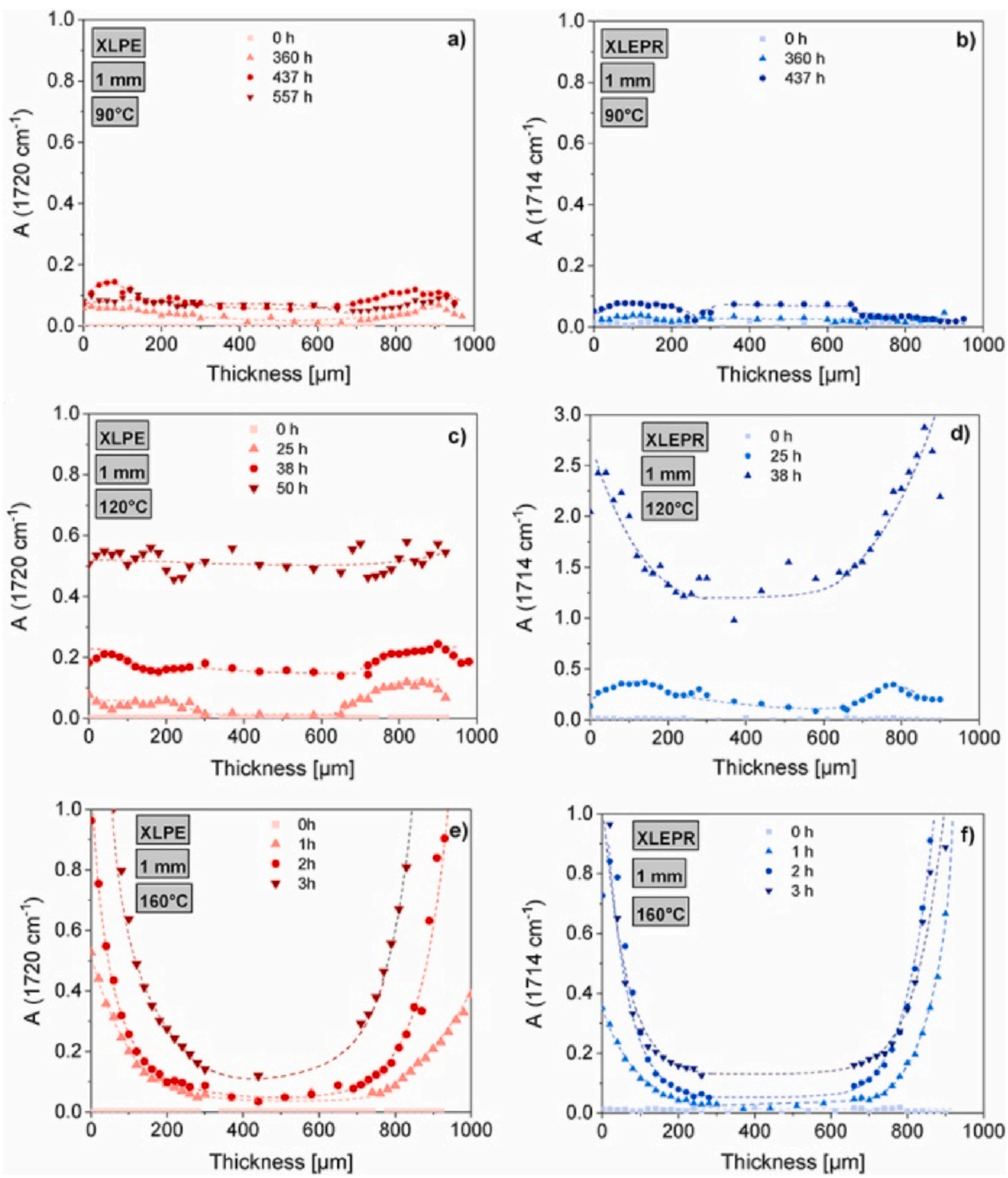

Fig. 12. The inhomogeneous degradation of cross-linked polyethylene and cross-linked ethylene propylene rubber [145].

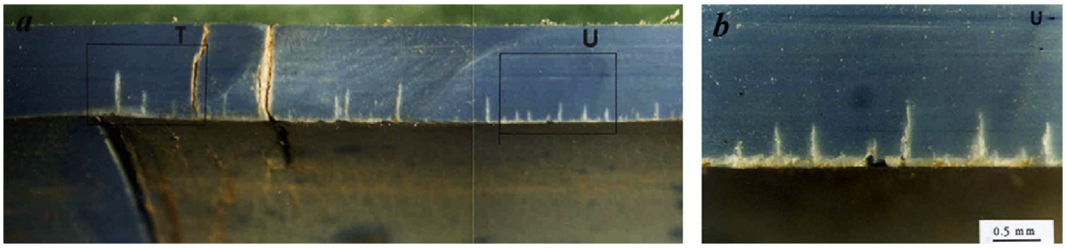

Fig. 13. Multiple cracks emanating from surface layer owing to DLO in PB pipe [132].

(3) Ignoring the scope of application

In many studies, chemical process controlling polymer oxidation has been formulated in terms of Arrhenius equation which is only valid in a limited temperature interval. It has been pointed out that when the temperature range was extended, a non-linear Arrhenius behavior was found for many materials in terms of oxidation rates [119,147]. It suggests that there is clearly a large error in predicting lifetime when we use the linear Arrhenius equation. Outside the applicable temperature range, the Arrhenius law will deviate from the reality, as shown in Fig. 14, which has been demonstrated experimentally [113,148]. The coupling of mechanical and chemical changes over a wide temperature range is the core of accelerated aging and lifetime prediction. Therefore, in order to make accurate lifetime prediction for PE pipes, all relevant chemical and mechanical change processes must be considered, but it inevitably increase the difficulty in the analysis of degradation rate and mechanical process. In addition, Arrhenius can only respond to one basic reaction process of the thermal-oxidative aging process in PE, while the oxidation of PE generally involves at least six basic reactions. Therefore, it may not be accurate to use the standardized Arrhenius law for such a complex case as thermo-oxidative aging [149].

5. Outlook

5.1. Multi-factor coupling impact on lifetime

The life of PE pipes is a function of the material, the environment, the mechanical state and their sub-factors (Eq. (21)), which is very difficult to be predicted due to the numerous factors. Only when all effects of these factors are known can a calculation of lifetime be justified. In other words, it is possible to achieve more reasonable and convincing lifetime prediction only if various factors of the external environment are taken into account completely. Therefore, in order to determine the service lifetime under the specific condition, it is necessary to establish a test method that includes the synthesis effect of various important sub-factors for application. In particular, attention should be paid to the second and third stages of the creep curve of PE pipes under long-term internal pressure, since these two stages actually control the service lifetime of PE pipes. However, the studies of current lifetime prediction often consider the thermo-oxidative aging only, which does not yet truly suitable for the operating environment. Therefore, it will be a trend to research pipe aging considering more factors. Moreover, not only multiple factors should be considered, but also the involved physical or chemical processes in the process of the above factors acting on the results, such as DLO or non-linear Arrhenius behavior. In addition, during the life cycle of PE pipes, whether the ductile or brittle failure occurs in pipes depends on which process is faster for the given surrounding medium, oxygen, external loads, temperature and the defect. Therefore, the lifetime prediction is a trend based on the coupled failure mechanism.

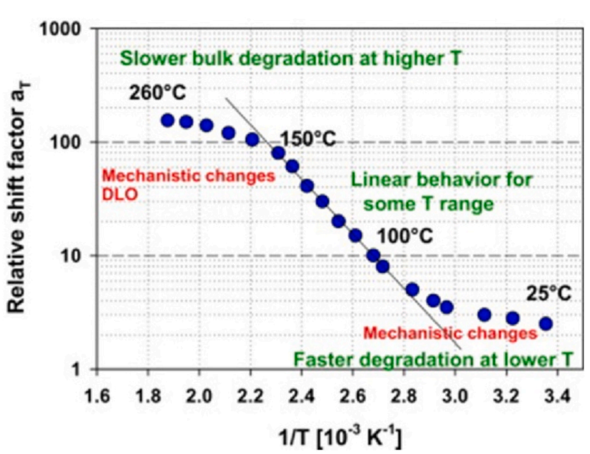

Fig. 14. Linear and nonlinear Arrhenius behavior of PE material [147].

$$life = f(material, loads, environment) \tag{21}$$

where, the material includes resin, additives, manufacturing process, etc. The environment includes gas, liquid, UV radiation, radioactive radiation, microorganisms, etc. The loads include internal pressure, external static/dynamic loads, notches, scratches, etc.

5.2. Life cycle prediction

As an important carrier of the lifeline engineering, PE pipes should also be put in a new demand for its lifetime prediction from the perspective of engineering application - total life cycle prediction. However, the current lifetime prediction accelerates the pipe failure by imposing a series of additional environmental conditions on PE pipes just produced, then, evaluates their lifetime based on mechanical or chemical methods. The lifetime predicted by these methods is the theoretical maximum that can be achieved, but the actual lifetime will be affected by uncontrollable factors such as the third party damage during operation. Therefore, in this case, the lifetime prediction of PE pipes may actually be a reliability issue involving external loads. In addition, the lifetime prediction for PE pipes is currently done for new pipes or pipes after artificially accelerated aging, while the prediction for in-service pipes is still lacking. However, pipeline operators might be more interested in the non-destructive lifetime prediction methods which can evaluate the remaining lifetime of PE pipes. Unfortunately, no relevant studies have been reported. Therefore, the non-destructive lifetime prediction for in-service pipes will definitely be the key point of development in the future, but there is still a long time before the application of these methods.

In addition, as the city gas pipe will gradually be laid in utility tunnel, the damage of PE pipes, joints or fittings caused by the third party damage, point loads, non-excavation or replacement technology will be avoided. However, the safety, repair and replacement of a large number of existing underground pipelines will form a long future coexistence with the safety problems of pipelines in the utility tunnel, which need be treated differently. Laying PE pipes in an individual tunnel of utility tunnel poses a new challenge for predicting the lifetime of PE pipes, where the factors affecting the pipe lifetime may only remain temperature, internal pressure and manufacturing defects. Therefore, it is more important to pay attention to its impact on the lifetime prediction of PE pipes due to environmental and load changes.

5.3. Improving accuracy of lifetime prediction

Accelerated test method is the core of lifetime prediction, and the uncertainty caused by accelerated test methods must be taken into account when combined with methods such as mechanical or chemical lifetime prediction. This uncertainty may be caused by a series of factors mentioned above. In terms of the micro-mechanism, the accelerated process is supposed to be caused by the pressure of external substances and the diffusion or absorption of oxygen within the crystal [10,150]. The accelerated test methods for PE pipes are closely related to the performance of the materials. On the one hand, the continuously improved accelerated test methods provide a reference for the reformation of pipe materials, and the performance of the materials is continuously improved from PE63 to the current P100-RC and even PE120 gradually. On the other hand, the continuously improved performance of materials will also lead to the improvement of the accelerated test methods to shorten the test time. The trend of improvement is to adjust the accelerated test environment to make it closer to the natural aging, which has the same failure mechanism as natural aging.

Compared to environmental stress, PE pipes are mainly subject to the accelerating effect of thermo-oxidation aging on the cracking process during long-term service. At the micro-level, the crack growth and the material aging are both related to the fracture of tie molecules, and the coupled effect of them might exist in service. On the one hand, the inhomogeneous aging of materials will lead to stress concentration and accelerate the crack initiation. On the other hand, the crack growth exposes the internal material of the PE pipe to the external environmental medium, which breaks the limit of DLO and accelerates the aging of internal material. With the improvement of PE materials quality, it is increasingly difficult to have an obvious stress-independent brittle failure (stage III in Fig. 1). The micro-mechanism of the pipe and the coupled effect of material aging and the stress crack are not considered in the current acceleration methods. In the hydrostatic test process, the material is affected by the hoop stress, temperature and thermo-oxidative aging, where the effect of material aging on pipe failure has been neglected, compared to the effect of hoop stress. In fact, the stress can accelerate the process of thermo-oxidative aging of PE pipes. It may be the case that PE molecular chains during aging are more susceptible to chain scission under the external stress, which increases the concentration of free radicals.

In order to solve these problems, a model based on chemo-mechanically coupled theory to study the coupled effect of the crack growth and material aging on PE pipes may be an effective approach. This coupled method might be an adequate way to characterize and model oxygen diffusion and polymer degradation. What's more, although the degraded layer can be simulated by this method, the brittle crack initiation and growth in stage III cannot be characterized or modeled. Thirty years ago, the crack layer theory had been developed to model the fracture process as the evolution of the system [151]. Recently, the modified CL model combined with stochastic approach has been established to describe the unique SCG of PE under creep and fatigue loading conditions [52,152,153]. In regard to chemo-mechanically coupled model and CL model, the first model can solve the problem of inhomogeneous degradation-degraded surface layer, and the other can characterize and simulate the brittle crack initiation and growth. In this way, combining these method will eliminate the empiricism in the current lifetime prediction methods and improve the accuracy.

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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