Defects Classification and Failure Modes of Electrofusion Joint for Connecting Polyethylene Pipes

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ABSTRACT: As electrofusion (EF) technology is widely used in connecting polyethylene (PE) pipes and other plastic pipes or composite pipes, research in safety assessment of EF joints has been of major concern. EF joints with defects are very common in practical applications. These defects may greatly reduce the mechanical performance of the EF joints and threat safety running of the pipeline system. To evaluate hazard of these defects and provide a basic understanding for the failure mechanism of EF joints, a comprehensive study on defects and failure modes is conducted in this work. The defects in EF joints are classified into four categories: poor fusion interface, over welding, voids, and structural deformity. The forming reasons of these defects are analyzed in detail. The mechanical properties of EF joint containing these defects are investigated by conducting peeling tests and sustained hydraulic pressure tests. Test results show that there are three main failure mode of EF joint under inner pressure, that is, cracking through the fusion interface, cracking through the fitting, and cracking through copper wire interface. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 124: 4070–4080, 2012

Key words: polyethylene pipe; defect; failure modes; electrofusion joint; strength

INTRODUCTION

Polyethylene (PE) pipe was initially introduced to transport natural gas in the 1960s, and now it has found widely use in many industries. Especially, in 2007, PE pipe was approved to be used for safety-related nuclear water pipe such as essential service water systems in the United States.[1] Because failure of these pipeline systems always cause heavy losses in economy as well as in lives, the safety of PE pipe has received more and more concern.

Researches have revealed that the safety of pipeline system mainly relies on the quality of welding joints, and investigations by PPDC (Plastic Pipe Database Committee) in 2010 show that 53% of the failure happened in the fitting, which is a key part of electrofusion (EF) joint. For this reason, improving the reliability of the EF joint is crucial to the safety of the pipeline system.

The safety issues of EF joint include appropriate design parameters (including structure and welding procedures), well installation, accurate inspection, and suitable assessment. Among the above issues, the design parameters have attracted most attentions. Bowman[2] comprehensively reviewed the EF welding process and divided it into four periods according to the formation procedure of the bonding strength between EF fitting and pipes. The influence of welding voltage, welding time, clearance between pipes, and fitting to the mechanical properties of EF joint was also analyzed in detail. By considering the temperature-dependent properties of PE and the variation of power input with the temperature of the resistance, Zheng[3] studied the influence of welding parameters to the temperature at the fusion interface during EF welding. Also, the appropriate cooling time after EF welding is determined by Higuchi.[4] Besides, the procedure that may affect the quality of EF joint during the installation process was discussed,[5] and the requirements for material, workmanship, and testing performance are prescribed by American Society of Testing and Materials (ASTM) standard.[6]

Comparing to the studies in determining the appropriate welding and installing condition, which has drawn lots of attention for decades, the nondestructive testing technique and safety assessment method for PE pipeline system are in the initial stage. To meet the requirement of the application in nuclear plant and gas transportation, researchers have studied several nondestructive technique to inspect the defects in pipe,[7] butt-fusion joint,[8,9] and EF joint[10–12] and found acceptable applicability. The performance of PE pipe system has also been studied intensively in respect of slow crack growth,[13–16] failure analysis,[17–19] and different loading

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conditions.[20–22] The defects are taken into consideration, and failure of PE pipe and joint is investigated. However, until very recently, few literatures have comprehensively reported the common characters of defects in EF joint and gave an answer to the question that what should be inspected in EF joint or how would the EF joint with defects fail during service. As a result, though the material grade of PE has upgraded for several generations, the intrinsic safety of EF joint is not improved in step because the failure modes and failure mechanism of EF joint in practical applications still remain inexplicable.

To investigate the drawbacks of the defects and find out how they cause the failure of EF joint, and also to provide a basic understanding for further study in the failure mechanism analysis of EF joint, a comprehensive defects classification method is proposed. The defects in EF joints are classified into four categories, and the forming reasons of these defects are analyzed in detail. The mechanical properties of EF joints containing these defects are investigated by conducting peeling tests and sustained hydraulic pressure tests. With these tests, three typical failure modes are observed.

EF WELDING PROCESS

A typical EF joint is shown in Figure 1. The EF joint consists of an EF fitting and two PE pipes inserted from both sides. On the inner surface of the EF fitting, a spiral conductive copper wire was prefixed. After the EF fitting is connected to a welding machine, heat is generated in the wire by Joule's effect and then diffuses into the surrounding PE. The PE around the wire gradually melts, and then the melting region slowly expands [see Fig. 2(1)]. After the melting region covers the interface, the joint is created. Usually, the welding process has to be continued until the melting region exceeds the interface for a certain distance. This is controlled by keeping the power of the EF welding machine for a specified fusion time (SFT), which is usually experimentally determined by the manufacturers by obtaining the best mechanical performance of EF joints after welding.[2]

To form a safe and sound EF joint, the pressure of the melting region should be hold at least at a specific value for a specific time, which is usually related to the base material of the pipe and fitting. Before EF welding, an interval between inner side of fitting and the outer side of pipe is required for the installation of pipes. During the welding process, the PE in the melting region, which is restricted by surrounding un-melted solid PE, tends to move to the inner and outer cold welding zone. When they reach the cold welding zone, the melt is cooled down and changes into solid. So, the remaining melt is bound within the melting region [see Fig. 2(2,3)]. Then, the

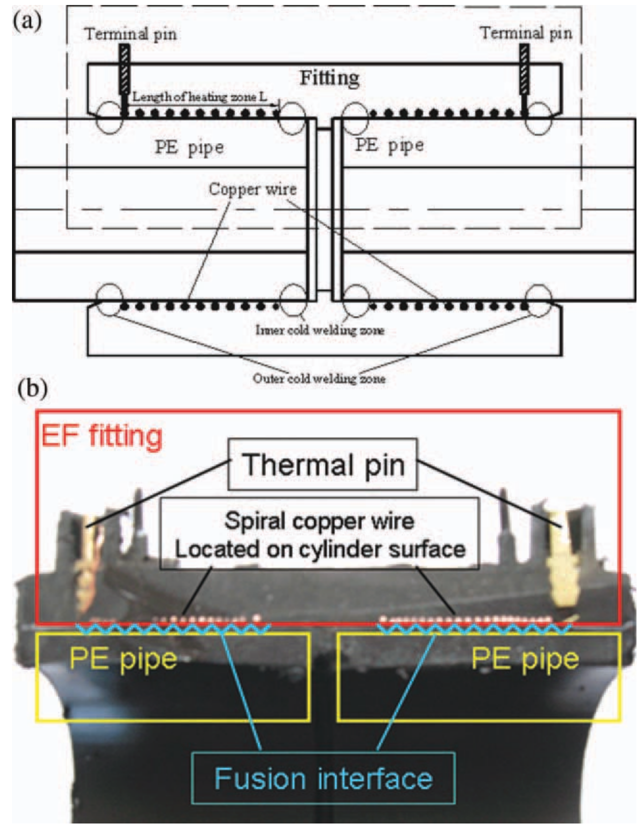

Figure 1 Electrofusion joint: (a) schematic sketch of EF joint; (b) structure of cross section of EF joint. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

PE continues to expand, and the welding pressure in the melted region slowly rises [see Fig. 2(4)].

Many factors such as oxide layer, dusty welding condition, misalignment, and incorrect parameters may affect the quality of EF joint.[23,24] Contamination will be produced when the welding interface contains oxide skin layer or dust and then develops into an initial crack, which finally results in the failure of joints. Misalignment and incorrect parameters may affect the entanglement of PE molecules, and thus the properties of the joint are weakened seriously. To conclude the drawbacks of these defects to the safety of EF joint, a systematically classification of the defects is necessary.

CLASSIFICATION OF DEFECTS

The classification method of the defects in EF joints was proposed by comprehensively considering the physical structure, inspectability, forming reasons, and possible failure mode resulted from the defects. The defects in EF joints were classified into four categories. The typical forming reasons, the structural characteristics, and the relating ultrasonic image were presented.

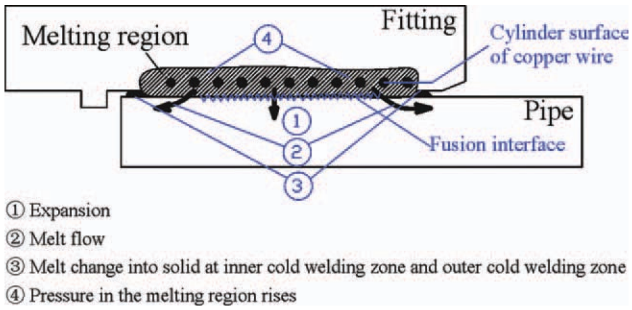

Figure 2 EF welding procedure. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Poor fusion interface

This type of defect occurs on the fusion interface between inner surface of EF fitting and outer surface of PE pipe. Three typical forming reasons for poor fusion interface are cold welding, unscraped oxide skin layer, and contamination of the fusion interface.

Cold welding

Cold welding is the most common defect in EF joint. The cold welding defect is usually caused by insufficient welding time or welding power. The joints of cold welding usually seem to be identical with normally welded joints, but the mechanical properties and long-time performance do not reach as those of good joints.[2,3]

In the peeling test, the cold welding joints usually fail at the fusion interface, and the peeling surface is sometimes brittle or semibrittle. The procedure and setup of peeling test are detailed in ISO 13954-1997.[25] The testing temperature is controlled at 23°C, and the peeling speed is 20 mm/min. The peeling energy of cold welding joint is not as much as that of normally welded joint.[2] As a result, the degree of cold welding, by considering its mechanical performance, can be characterized by the ratio of peeling energy of cold welding joint to that of normally welded joint. However, in practical applications, it is much convenient to characterize the degree of cold welding by the proportion of the lack welding energy, as expressed by the following equation:

$$H = 1 - \frac{Q}{Q_0}$$

where H represents the degree of cold welding, Q is the welding energy of the cold welding joint (J), Q_0 is the normally weld energy of the specified type of EF joint (J).

Serious cold welding joint will cause nonfusion at the welding interface. Nonfusion joint will fail immediately when pressurized with the working load and results in a leakage of the transported medium through the fusion interface. The cold welding joints with $H = 40\%$ and $H = 80\%$ are shown in Figure 3.

Unscraped oxide skin

Allen et al.[23] reported that oxidation of the pipe occurs predominantly on the outer surface and to a lesser extent on the bore, often with little or no change in the central layers. If the pipes have

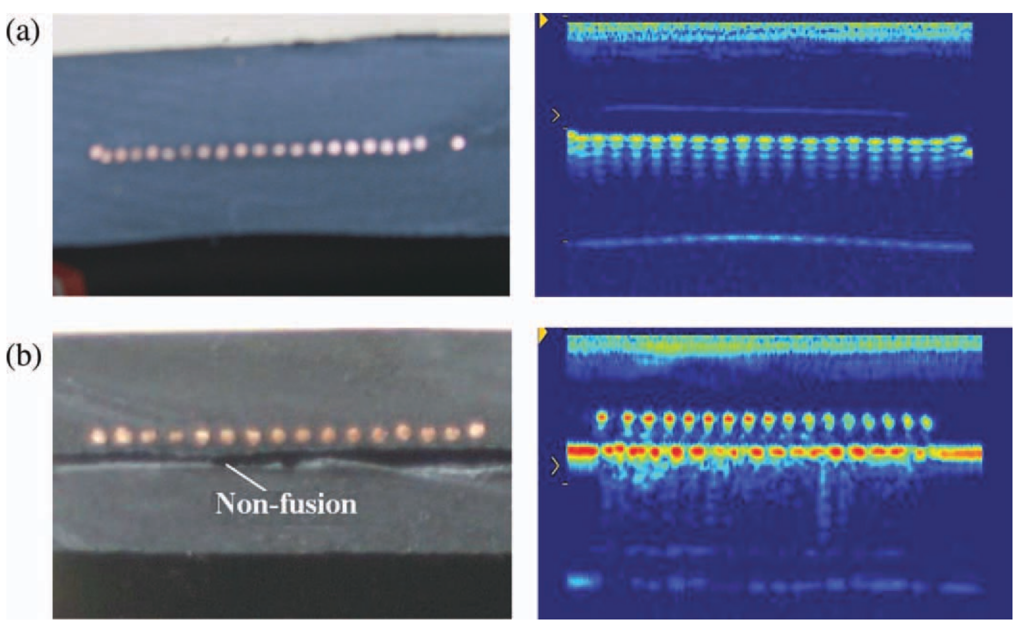

Figure 3 Cross section view of cold welding joint and ultrasonic image: (a) cold welding joint with $H = 40\%$. Cross section view of cold welding joint and ultrasonic image: (b) cold welding joint with $H = 80\%$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

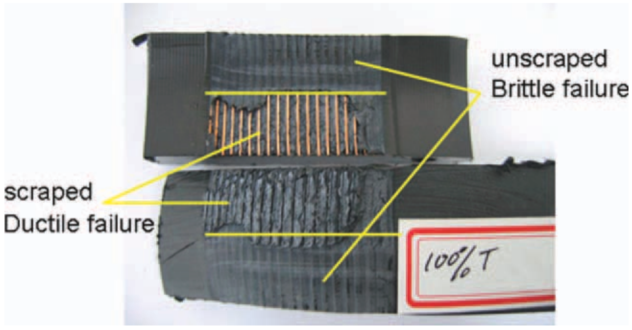

Figure 4 Failure of EF joint containing both scraped and unscraped oxide skin after peeling test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

experienced natural exposure for some time, the outer surface should be scraped for about 0.5 mm or more to get rid of the oxidation layer. Parallel cleavage test results of EF joint of gas pipes showed that the maximum load and the fracture toughness of the welding pipe without scraping oxide layer are much less than those of scraped pipe, respectively. And brittle failure mode, mixed brittle, and ductile failure mode of unscraped EF joints are observed in the test comparing to ductile failure mode of scraped joint.

By conducting peeling test on EF joints with partially scrapped oxide layer, it is found that the unscraped region failed at the fusion interface with brittle failure surface, and the scraped region failed at the surface of copper wire with ductile failure surface. The result reveals that the fusion interface was not properly formed due to the obstruction of the oxide layer, as shown in Figure 4. Thus, the oxide layer removal is a necessary step in the welding specifications. However, this scraping process is usually boiling and tedious and sometimes ignored by welding operators. As a result, some portion of the welding surface is not fully scraped, or the scraped layer is not scraped to the required depth, which would lead to a poor fusion interface defect.

Contamination of the fusion interface

The most usual contaminations at the interface of the outer pipe wall and inner fitting wall are dust and leaves. This defect in EF joint also occurred in the stage of pipe preparation. After the scratching of oxide skin layer, the pipe should be inserted into the fittings at once to avoid the possibility of pollution of the welding surface.

The defect of contamination of the fusion interface is physically equivalent to shorten the effective bonding length of fusion interface. An artificially prepared EF joint containing contamination of fusion interface is shown in Figure 5. Generally, uniform dispersion of contamination usually results in a brittle failure of the welding interface, and the perniciousness of other localized contamination defect is not only related to their length (maximum dimension of the facial defect in the axial direction), but also related to their positions. For example, it has been reported that the contamination of the fusion interface connecting to the inner cold welding zone is much more dangerous when compared with same defect located at middle welding zone or connecting to the outer cold welding zone.[26]

Voids

Voids in EF joint refer to volumetric defects in the vicinity of fusion interface and the copper wire. The cross section view and related ultrasonic image of EF joint containing voids are shown in Figure 6. The defect of voids would make structural discontinuities in EF joint and cause stress concentration, which may further lead to initiate crack.

ASTM considers the voids as a phenomenon of the EF process, due to trapped air and shrinking during the cooling process after the joint is made.[6] Besides, the gasification of PE material and the generation of steam because of the residual water in PE

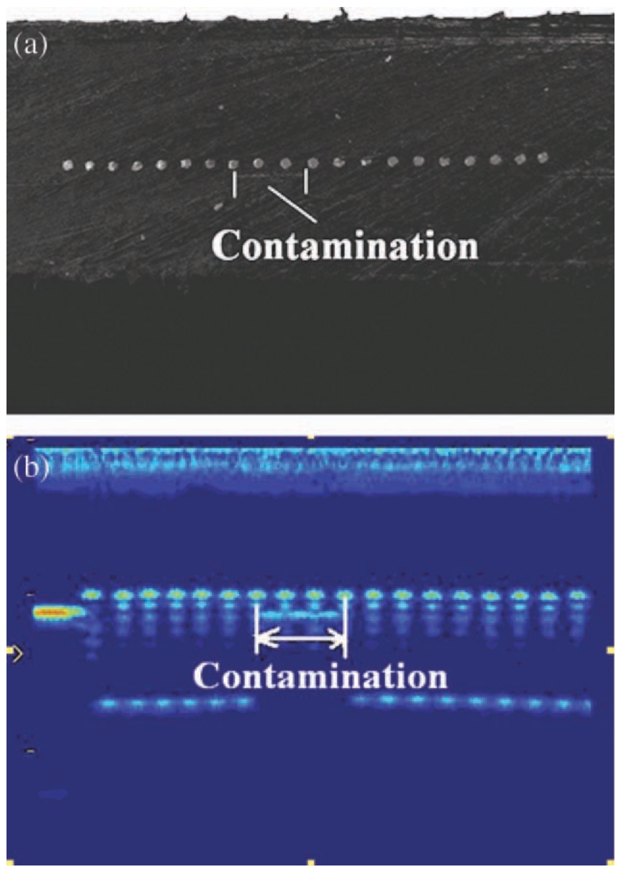

Figure 5 Contamination of fusion interface in EF joint: (a) cross section profile; (b) ultrasonic image. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

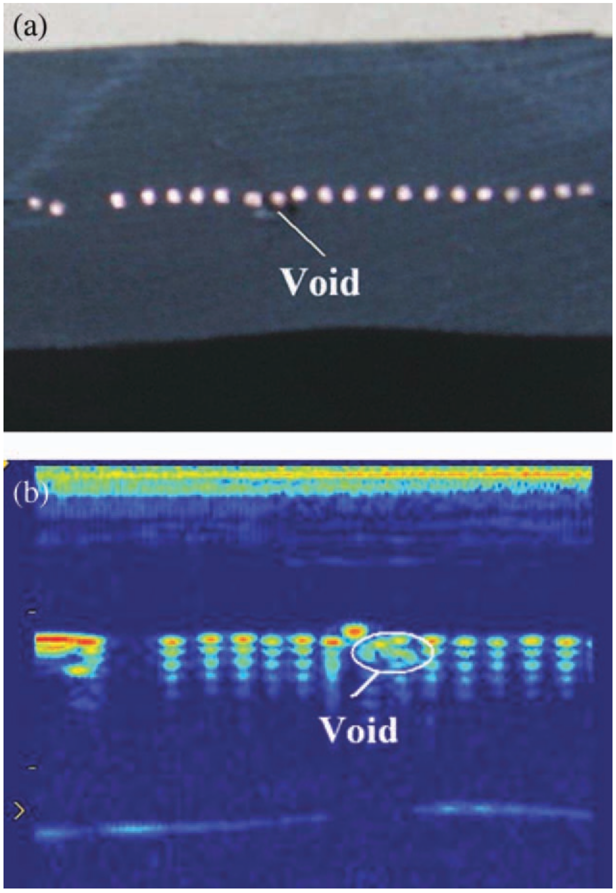

Figure 6 EF joint with defect of voids: (a) cross section profile; (b) ultrasonic image. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

material or wet contamination at the outer surface of the pipe are also major causes of voids.

Structural deformity

The defects of structural deformity refer to the EF joint failed to keep an expected structure after welding due to in proper operation, which includes wire dislocation, misalignment, and inadequate insertion.

Wire dislocation means that the heating wire is not in a line any more after welding, as shown in Figures 7 and 8. Wire dislocation includes horizontal dislocation, vertical dislocation, and dislocation in both directions. The vertical dislocation of copper wire is due to irregular flow of the melted PE material, which was mainly caused by excessive pressure produced by the expansion of melting PE. This type of defect is related to improper design clearance between inner fitting and outer pipe wall, which usually happens in the EF joints of small diameter PE pipes.

If two pipes are inadequately inserted into the EF fitting, during the welding process, the melted PE would flow out of the inner cold welding zone and release the pressure of welding region. As a result, the effective bonding length is shortened, and the strength of bonded region may also be weakened because of the decreased pressure.

The defects of inadequate insertion are usually accompanied with horizontal wire dislocation. As the melted PE of fitting flow out of the inner cold zone without obstruction, it displaces the copper wire, shown in Figure 9.

Over welding

Over welding is caused by excessively high temperature around the copper wire due to too much input energy and results in the degradation of PE close to this region. It is possible that the degradation of PE would occur in the vicinity of the copper wire. During peeling test, the joint fails through the surface of copper wire, and the failure surface is brittle, with carbon-like dusty material accumulated on the surface, as shown in Figure 10. Physically, the existence of copper wire destroys the integrity of the EF joint and causes a reduction of mechanical performance in the axial direction, which makes this region a natural weak point of the EF joints.

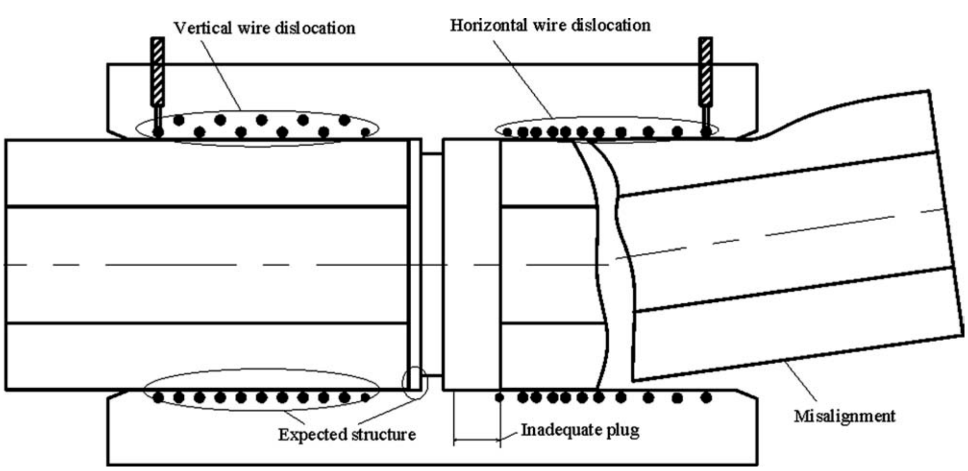

Figure 7 Sketch of structure deformity defect.

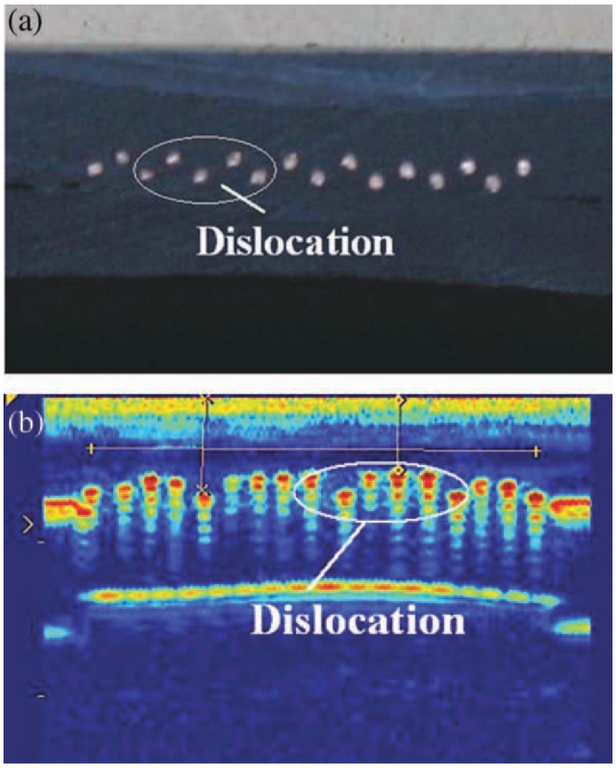

Figure 8 EF joint with defect of wire dislocation: (a) vertical dislocation of copper wire; (b) ultrasonic image. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

If the EF joints are properly welded, they would obtain enough strength to sustain the inner pressure. However, when the degradation of PE around the copper wire happened because of over welding, the ability to resist the crack growth along the axial direction near the copper wire is diminished and possibly causes a failure along this surface.

MECHANICAL PROPERTIES OF EF JOINT WITH DEFECTS

The welding quality and mechanical properties of EF joint consist of two aspects: one is the bonding strength of the welded region, and the other one is the area of the welded region. To study the influence of these two factors, two types of artificial defects in EF joint were made: one uses the Teflon adhesive tape to hinder the contact of fitting and pipe, so as to manually control the area of the welded region. And for the other aspect, we made the EF joint with different welding time to weaken the bonding strength of the fusion interface between inner fitting wall and outer pipe wall or the surface of copper wire.

Preparation of EF joints containing defects

The lack of fusion interface defect was prepared by obstructing the inner fitting wall and the outer pipe wall with a Teflon adhesive tape. The total fusion region is divided into three zones: inner fusion zone, middle fusion zone, and outer fusion zone, respectively, as shown in Figure 11. There is cold welding zone on both sides of fusion region, respectively. The Teflon adhesive tape is glued around the entire circumference to the outer surface of the pipe wall after scratching and cleaning of the pipe surface. The Teflon adhesive tape is placed at different fusion zone to create defect at different position, as shown in Figure 12.

The pipe and fittings used in the test are D90 (diameter is 90 mm) PE80 (material grade) SDR11 (standard diameter ratio, which is the ratio of diameter to thickness) series. The length of total fusion region in fittings is 36 mm. Some parts of the fusion zone are covered by the Teflon adhesive tape to create specified fusion region in EF joint, shown in Figure 12. The fusion region are sized of 3, 5, 7, 10, and

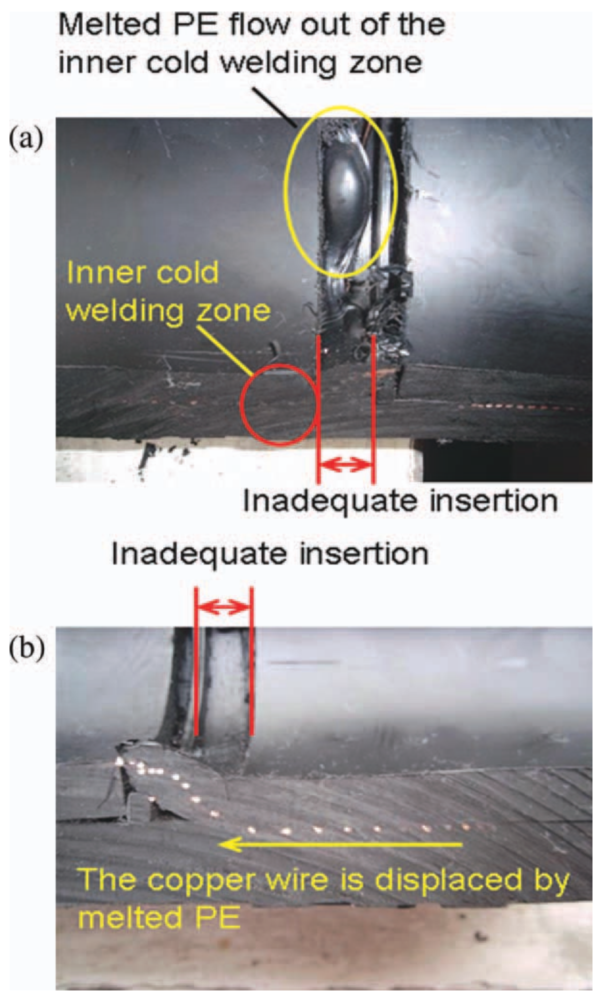

Figure 9 Horizontal wire dislocation resulted from inadequate insertion: (a) melted PE flow out of the inner cold welding zone; (b) copper wire displaced by melted PE. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

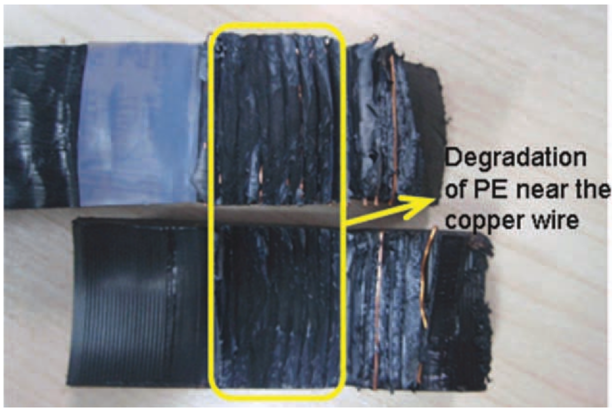

Figure 10 Brittle failure interface of over welding EF joint after peeling. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

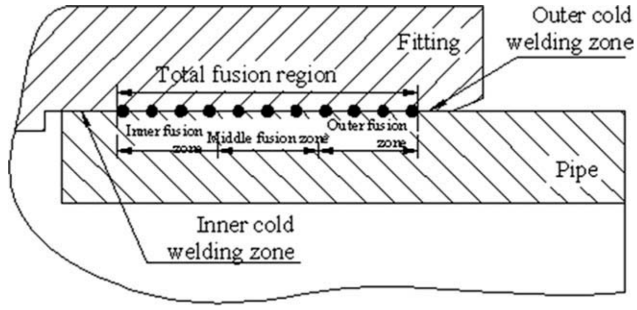

Figure 11 Fusion region of EF joint.

13 mm and located in the inner fusion zone, middle fusion zone, and outer fusion zone, respectively.

The bonding strength of the fusion interface has been proven to relate with the welding time.[27] There are four stages of EF joint during welding named as incubation period, joint formation and consolidation, plateau region, and degradation, respectively.[2] The proper welding time of EF joint should be in the region of plateau region. If the EF welding process finishes before coming into the plateau region, the welded joint would contain cold welding defect. Else, if the EF welding time passed the plateau region, this will cause over welding defect. The artificial cold welding and over welding defect joint

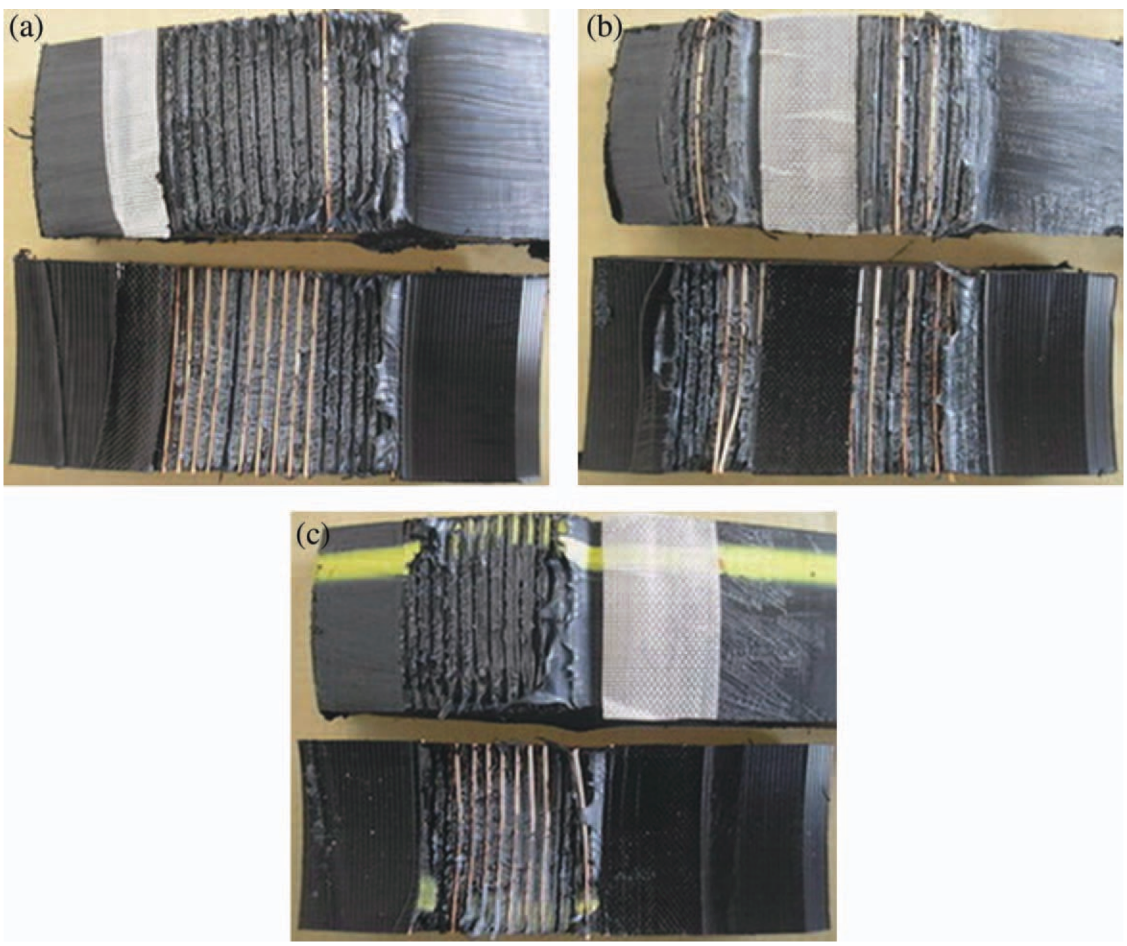

Figure 12 Artificial defects of contamination of fusion interface: (a) defect in the inner fusion zone; (b) defect in the middle fusion zone; (c) defect in the outer fusion zone. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE I
Testing Results of Sustained Hydraulic Pressure Test

Length of melted region (mm)		3			5			7			10			13	
Size of defect (mm)		33			31			29			26			23	
Position of melted region	O	M	I	O	M	I	O	M	I	O	M	I	O	M	I
Failure time/h	[a]	211	[a]	[a]	[a]	[a]	[a]	[a]	[a]	275	[a]	[a]	[a]	[a]	[a]
Failure position	[a]	Fitting	[a]	[a]	[a]	[a]	[a]	[a]	[a]	Fitting	[a]	[a]	[a]	[a]	[a]
Failure mode	[a]	Cracking	[a]	[a]	[a]	[a]	[a]	[a]	[a]	Cracking	[a]	[a]	[a]	[a]	[a]

[a] Means that the test specimen survived after test. O, M, and I represent the outer welding zone, middle welding zone, and inner welding zone, respectively.

were prepared by applying different welding time during EF welding. The SFT of D90 EF fitting is 110 s, and the welding voltage is controlled at a constant value of 39.5 V. The cold welding joint is welded as 33, 44, and 66 s, respectively, and the over welding joint is welded as 132 and 154 s, respectively.

Test method

The prepared specimen is put into sustained hydraulic pressure test according to ISO 4437,[28] the testing temperature is 80°C, and the hydraulic pressure is 0.9 MPa. The test last for 825 h if the testing specimen did not fail in the testing process.

Results and discussion

The testing result of EF joint containing contamination defect is listed in Table I. Most of the EF joint survive 825 h, except for two joints, which failed as cracking through fitting, as shown in Figure 13. The crack in EF fittings initiates from the first copper wire closest to the inner cold welding zone and propagates at an angle of ∼ 70° through the entire fitting. No obvious deformation was observed.

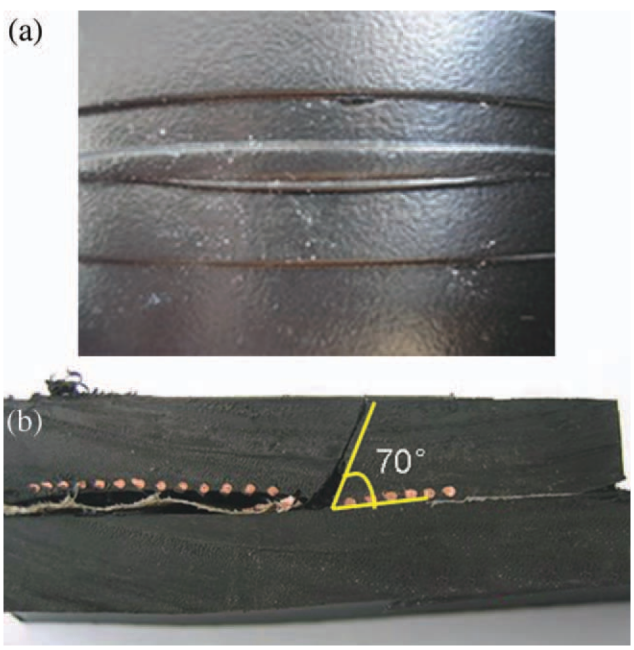

Figure 13 Cracking through the fitting (a) outer surface of fitting; (b) cross session of EF fitting. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Most of the EF joints containing contamination defect survived 825 h in 80°C sustained hydraulic pressure test. Even the melted region is only 3 mm in length, and two of the three testing samples did not fail. The only failed specimen during the sustained test yields a crack through the fitting wall, rather than through the fusion interface.

Actually, when the welded joint was subjected to inner pressure, the pipes were about to expand. And this deformation was restricted by the outer fitting by applying compression stress on the pipe-fitting interface. So the main stress at the welding interface is compression stress, which is about to compress the gap between the inner surface of the fitting and the outer surface of the pipe. From this point of view, the EF joint is relatively safe for the main working load provide a protection for fusion interface.

The testing results of EF joints with cold welding defect are listed in Table II. It was found that when the welding time is 22 s, the joint was not formed. And though the joint has been welded together with the welding time of 33 s, it failed immediately when the testing pressure rise. According to the results of our previously developed temperature analysis model,[3] when welding time is 22 s, temperature at the pipe-fitting interface is much less than that at the melting point of PE. And when welding time last for 33 s, temperature at the fusion interface is just surpassed

TABLE II
Sustained Pressure Test of Cold Welding and Overwelding Joint

t_{EF} (s)	Failure mode	Duration
20% t_o	Joint is not formed	
30% t_o	Crack through the fusion interface	0
40% t_o	Crack through the fusion interface	47 h
60% t_o	[a]	[a]
140% t_o	[a]	[a]

[a] The testing specimen survived for 825 h.

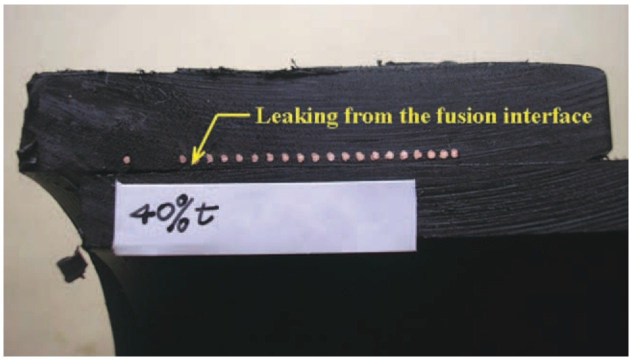

Figure 14 Failure of cracking through the fusion interface. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the melting point of PE, and EF joint is just formed without developing any strength. So, it failed immediately when subjected to the inner pressure.

The EF joint with 44 s welding time survived 47 h during the test. The joint failed as cracking through the fusion interface, as shown in Figure 14. This is a typical cold welding joint. They just appear the same with normally welded joint, but the strength does not reach that of normally welded joint. Usually, the pipeline system will be charged with pressure about 50% higher than its working pressure to test its quality. For steel pipes, the joints usually fail immediately if they contain serious defect. But for EF joints of PE or other plastic pipes, joints containing defect may survive, especially for such defect as cold welding. It is difficult to evaluate the influence of cold welding defect to the structural integrity and actual life of EF joint. However, the degree of cold welding can now be precisely measure by ultrasonic method.[12] And this provides a possibility to access the unqualified joint based on NDT technique.

The EF joint with 66 and 154 s welding time did not fail in the sustained hydraulic pressure test within 825 h. The results mean that the EF joint with welding time of 66 and 154 s may have developed enough strength to hold the inner pressure for a relatively long period of time. As was found by Bowman,[2] there is a plateau time region of EF welding process. Our experimental results not only proved the existence of the plateau time region, but also showed that EF welding has a relatively wide welding time window. So, it is easier for the manufacturer of EF fitting to select proper welding parameters for their products, and the welding quality will not be easily affected by fluctuation of welding time or welding power.

Failure modes of EF joint

As shown in Figure 15, the main effect of inner pressure applied in the inner surface of pipe is to compress the gaps between the outer surface of pipe and the inner surface of fitting. However, the inner pressure would also apply on the inner cold welding zone, which are about to peel the middle part of the fitting from the pipe. This peeling effect will cause three risks in EF joint under inner pressure: the first one is to cause the cold welding joint to fail at the fusion interface; second, it causes a crack propagation through the fitting wall with an angle of over 45° to the axis of the pipe; and third, it may cause a failure at the surface of the copper wire in over welding joint, which was shown in Figure 15. Although the third failure mode has not yet been experimentally observed with sustained pressure test, according to "Over welding" section, if the EF joint was serious over welded and caused the material along the heating wire to degrade seriously, the strength in this part would be very poor and become the weak point of the whole joint.

The failure mode of cracking through the fitting wall was usually due to oversized inner cold welding zone, and this cause a stress concentration in the copper wire closest to the inner cold welding zone and finally initiate a crack. Although most of the EF joints with 3–13 mm fusion length survived in sustained pressure test, all the contamination defect connecting to the inner welding zone are about to fail by cracking through the fitting, for the initial cracks are observed in most of these EF joint after sectioning, as shown in Figure 16.

The failure through the fitting is usually due to incorrect design or improper installation in practical application. Too much length of the inner cold welding zone would cause a stress concentration in the corner of the first copper wire and result in a crack initiation and then propagation of cracks. On the other hand, too small length of the inner cold welding zone would cause the melted PE flow out of the melting region and result in a pressure drop in the welding region. So, the proper length of the inner cold welding zone should be carefully determined when designing the structure of EF fittings.

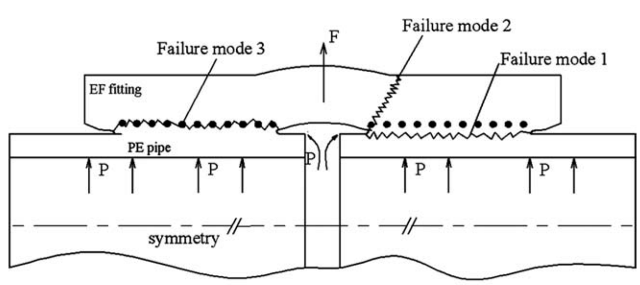

Figure 15 Failure modes of EF joint.

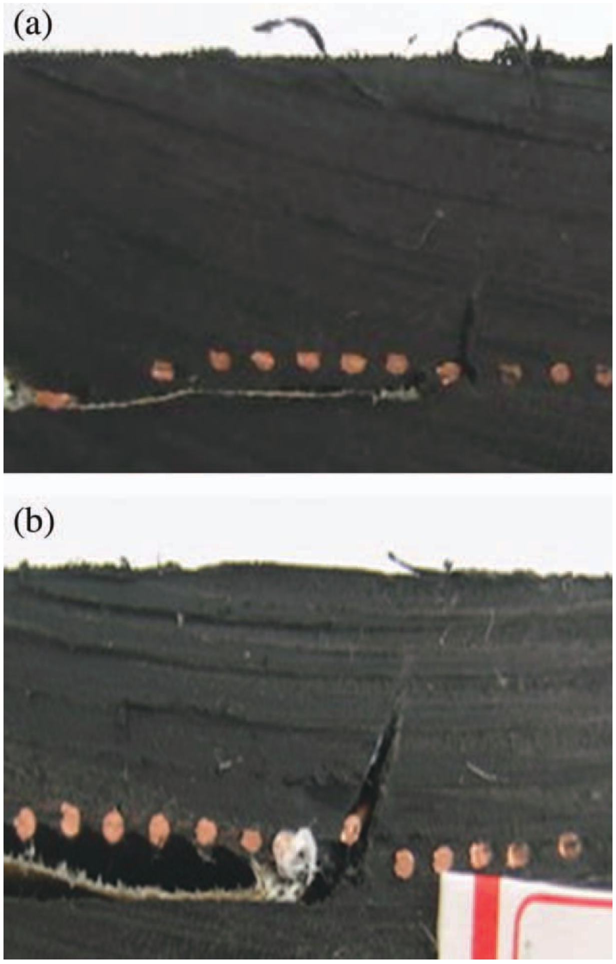

Figure 16 Crack development at the copper wire closest to the inner cold welding zone: (a) crack initiation; (b) crack propagation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Besides, the failure is also likely to occur at the fusion interface or surface through the copper wire. Failure at the fusion interface is due to insufficient bonding strength between pipes and fitting. Failure at the surface through the copper wire is because of the degradation of PE caused by high temperature near copper wire and the discontinuity caused by separation of copper wire. To compare the bonding strength between fusion interface and the surface through the copper wire and to find out the weaker part of the failure surface, peeling test according to ISO 13954-1997[25] is applied.

Three typical failure surfaces of peeling test are observed: brittle failure surface from the fusion interface, which is made with welding time of 30% of the SFT, as shown in Figure 17; ductile failure surface from the surface of copper wire, which is made with welding time of the SFT, as shown in Figure 18; and brittle failure surface from the surface of copper wire, which is made with welding time of

Figure 17 Failure from the fusion interface. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

140% of the SFT, as shown in Figure 10. However, there are also mixed failure modes combining the above three types.

Bowman defined five grade of failure type: no joint, low strength, stress whitened, ductile, and highly ductile.[2] It should be emphasized that the failure type of stress whitened defined by Bowman, which is produced by 55% of the SFT, is characterized by flat failure surface, some observed wire imprint and stress whiten. This type of failure is similar to the condition of equal strength between fusion interface and surface of copper wire.

If the welding energy input during welding process is not enough to join the fitting and pipes firmly, the joint will fail at the fusion interface during peeling test. As the welding time increases, the weak part of EF joint transferred from the pipe-fitting interface to the surface of copper wire.[2] When

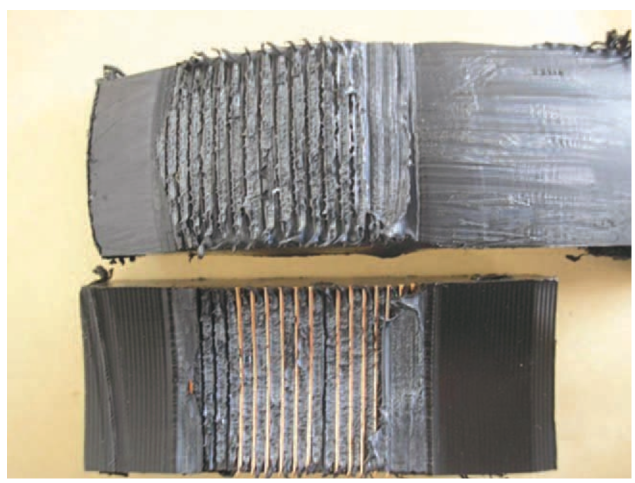

Figure 18 Failure from the surface of copper wire. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the welding time is set to a value longer than 55% of the SFT, EF joint fails from the surface of copper wire, which means that the fusion interface is safer than the surface of copper wire. When the welding time is set to a value longer than 140% of the SFT, the PE material in the vicinity of copper wire may degrade and produce a weak part at the surface of copper wire. There is a time window between 55 and 140% of the SFT, within which the strength of the EF welding joint maintains at a constant value.

CONCLUSIONS

The defects in EF joints of PE pipes are classified as poor fusion interface, voids, structural deformity, and over welding. Three main failure mode of EF joint under inner pressure are cracking through the fusion interface, cracking through the fitting, and cracking through copper wire interface. These three failure modes are typically related to the length of cold welding zone and the input welding energy.

Failure mode of cracking through the fitting wall is due to oversized inner cold welding zone, which results in a stress concentration in the copper wire closest to the inner cold welding zone. So, proper length of inner cold welding zone should be carefully determined to prevent either cracking through the fitting because of too long inner cold welding zone or wire dislocation due to too short inner cold welding zone.

Implantation of copper wire causes discontinuity of the EF joint and makes the surface at the copper wire a weak point in the structure EF joint. If the welding time exceeds 140% of the SFT, the bonding strength at the surface of copper wire drops quickly because of degradation of PE near the copper wire.

Bonding strength of the fusion interface is greater than that at the surface of copper wire in a relatively wide welding time range from about 55–140% of the SFT. However, if degree of cold welding defect (H) exceeds about 45%, the bonding strength of fusion interface is weakened.

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