Stages in the Development of the Strength of Electrofusion Joints

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INTRODUCTION

Fusion joints are incorporated into plastics structures that sustain significant loads for long periods of time. In these applications the fusion joints can determine the strength and/or longevity of the total structure, so joint strength must be optimised. This can be achieved either by trial and error (combined with experience) or by understanding the mechanism by which fusion joints aquire their strength. If the latter route is followed, together with numerical modeling of the heat flux and material deformation and flow, the engineer has powerfull tools to optimise the design and process variables of fusion joining.

For plastics there is a wide range of fusion joining processes. Electrofusion (E/F) joining is one of the simplest because the heating and cooling rates are relatively slow, the fusion times long and there is little melt flow. Thus E/F joining is ameanable for studying the mechanism of joint formation, and reported here is a proposed mechanism to explain strength development in E/F joints. The study is focused on E/F joining of polyethylene (PE) pressure pipes. This choice reflects the widespread and successful use of E/F jointing technologies in pressure pipe applications, where the joints must be fluid tight and capable of sustaining loads for typically 50 years. The paper thus commences with a description of E/F couplers as used for fusion joining PE pressure pipes.

ELECTROFUSION COUPLERS FOR JOINING PIPES

The bore diameter of an E/F coupler is essentially constant along its length, with the bore diameter usually larger than the diameter of the pipe for which it is designed (1). E/F couplers have two separate fusion zones, they have center pipe stops, and they have four cold zones (two at the center and two at the ends of the coupler) see Fig. 1. The heat to effect the fusion joint is created by passing a current through the resistance heating wires via the terminal pins. The heating wires are usually covered or coated with the polymer used to mold the body of the fitting.

Three critical pipe preparation steps must be followed for E/F joining. First, pipe ends must be cut square and pushed to the center of the fitting to allow the center cold zones to function. Second, the pipes must be thoroughly scraped to remove any dirt and contamination which would otherwise remain on the fusion interface. Finally, the pipes must be clamped securely during fusion and cooling to reduce the relative movement between the pipes and coupler, so allowing the formation of a strong joint.

Having identified the basic design of E/F couplers, and iterated the necessary pipe preparation steps, the literature relevant to the proposed model is reviewed. The most pertinent literature is the recently published studies on strength development in E/F joints (2) (3) (4) (5), and this is reviewed first. In the discussion section other work on plastics joining and processing is added to advance a possible mechanism for the process of E/F joining.

STRENGTH DEVELOPMENT IN ELECTROFUSION JOINING

With E/F joining progressively increasing the fusion time increases the energy input into the joint. It is to be expected that the joint strength (when cool) increases with increasing fusion time, so by following fusion time - joint strength relationships a better understanding of the mechanism of E/F joining should follow. Four studies have been published recently on strength development, two using coupons cut from joints made with E/F pipe couplers, and two with a simulated E/F pipe joint.

Strength Development with Pipe Couplers

A fracture mechanics approach to assess joint strength has been used by Marshall and Cosgrove (2). A double cantilever beam cleavage test allowed the calculation of the toughness parameter Kc by recording the peak load. By this route the increase in joint strength with fusion time was followed (see Fig. 2); the work was undertaken with an unidentified coupler joined under ill-defined conditions. Note that the use of the toughness parameter Kc for ductile failures is strictly not valid (2).

Bowman (3) has recorded the development of joint strength with fusion time by measuring the energy required to peel part of a coupler from the adjoining pipe. This peel energy has been shown to correlate well with a quantitative measure of the ductility seen on the fracture surface of the failed peel sample (3) (6). For a 90mm coupler fused at -

5°C using minimum power (7), Fig. 3 (a) records the development in joint strength with fusion time by anotating the results of individual peel tests. Fig 3 (b) for a 180mm coupler joint fused under similar conditions records the average joint strength (of 4 to 8 peel samples at each fusion time) as a function of fusion time. Also recorded in Fig. 3 (b) is the coefficient of variation and at each fusion time, and the percentage of peel samples that failed in a totally brittle mode. Note that brittleness varies around a coupler, so that some peel samples can be brittle and some ductile from the same coupler.

Strength Development with Simulated Joints

Nishimura et al (4) in 1989 set out the design of a simulated E/F joint and the sample shape used to test joint strength. The same authors presented more data in 1991 (5) to record how fusion time influences joint strength, and they used two measures of joint strength. The tensile strength of a notched sample was recorded as a function of heating time for a range of supplied wattages (from 3 to 8.5 W/cm2); and Fig. 4 records two of these plots.

The second method Masaki el al (5) used to measure joint strength was an (3) elevated temperature lifetime test. This induced failure by the slow propagation of a brittle crack (8). For a stress of 3.9MPa, Fig.5 records how the lifetime of the joint varied with fusion time, again for two supplied wattages. Note that data was presented at the conference showing good correlations between the work on simulated E/F joints and E/F coupler pipe joints, but this was not included in the paper cited here (5).

General Observations on Strength Development

Four studies, using four different measures of joint strength (Kc, peel energy, tensile strength and elevated temperature lifetime) have produced broadly similar curves of joint strength against fusion time, see Figs. 2,3,4 and 5. This similarity allows the E/F joining process to be divided into four stages, with an additional phase of degradation if the fusion process is carried on too long. The various stages are;

a) INCUBATION PERIOD. At the start and in the early stages of the fusion process the joint has no strength. This is the incubation phase.

b) JOINT FORMATION. The point at which the joint aquires strength is the joint formation stage. Joint strength often increases rapidly over a short period of time in the joint formation phase.

c) JOINT CONSOLIDATION. Once the joint is formed, joint strength increases with increasing fusion time. The failure mode also changes from brittle at short fusion times to increasingly ductile with increasing fusion time.

d) (JOINT DEGRADATION). The title of this phase in the joining process is put in brackets because it is not observed with good fusion processes. It will, however, be seen with fusion times that are too long. When degradation occurs, it is the PE resin that degrades due to extended exposure to high temperatures.

e) COOLING. After the current to the heating coils has ceased to flow, the joint cools, the PE resin crystallizes and the joint aquires real strength.

Using the above framework, the key stages in the E/F joining process are discussed separately.

DISCUSSION

Incubation Period

When an E/F joint is first assembled there is, for the vast majority of couplers used in the field, a measurable gap between the pipe and coupler, see (1) and Fig. 6 (a). At the start of the incubation period the supplied energy heats the coupler, the PE component of which then expands to fill the gap, see Fig. 6(b). The gap filling process is efficient as PE expands about 20% in going from 20 to 250°C. Once the coupler is in contact with the pipe, both are heated. The incubation period ends as the PE on the pipe is taken above the crystalline melting temperature, Tm. For pipe grade PE resins Tm is in the range 120 to 135°C. The joint has no strength for fusion times within the incubation period, but the two surfaces to be joined are wetted.

Joint Formation

Energy supplied to the joint raises the resin temperature above Tm for polymer on the bore of the fitting and the outside of the pipe. Provided that there was no contamination on the joint interface prior to fusion (that is the pipe was scraped), the melts from the fitting bore and pipe combine to form a melt pool at the fusion interface, see Fig. 6 (c). A stable melt pool, which is critical to joint formation, is facilitated in its formation by the cold zones and the low thermal conductivity of PE resins. The cold zones freeze-off any polymer that, due to melt pressure at the joint (4), attempts to extrude out (see Fig. 6 (c)). The low thermal conductivity of PE restricts resin melting to polymer close to the fusion zone. A cold cage thus contains the stable melt pool.

The joint strength at the joint formation stage is now real but relatively low, see Figs. 2,3,4 and 5, and the failures are brittle (2). It is postulated these low strength brittle failures are due to a limited concentration of macromolecular chain linkages across the joint interface, specifically low concentrations of low molecular weight tie molecules and amorphous chain entanglements at the joint, see reference (9). The low concentration of these species arises from limited molecular self-diffusion across the fusion interface. Support for this comes from the observation that with bulk semicrystalline thermoplastics (such as PE) brittle fracture is associated with low concentrations of tie molecules (10). The evidence of increasing joint strength with fusion time, discussed in the next section, supports the above proposal on the importance of molecular diffusion and tie molecule concentration.

Joint Consolidation

Four different measures of strength have shown joint strength to increase with increasing fusion times above and beyond the joint formation stage, see Figs. 2,3, 4 and 5. In addition the failure mode changes from brittle along the fusion interface to ductile through the resistance heating wire plane, (2) (3) and Fig. 3 (b). It is proposed that increasing the fusion time led to an increasing melt temperature (11) which increased diffusion to increase the concentration of tie molecules across the fusion interface. In particular the high molecular weight fraction is allowed to diffuse across the boundary, this increased diffusion being facilitated by time and temperature (9) (12). The diffusion of the high molecular weight fraction across the joint leads to increases in the molecular weight of the polymer that can be considered to constitute the E/F joint. These changes in the fusion interface macromolecular structure give rise to the observed increases in joint strength and joint ductility with increasing fusion time.

Support for the above proposal comes in part from knowledge of the (6) mechanical behaviour of bulk PE resins. With PE materials the toughness increases and the tendancy to brittle failure decreases with

increasing molecular weight, particularly of the high molecular weight tail (13). The elevated temperature stress rupture lifetimes of PE materials also increase as the high molecular weight tail is increased (14) and the resin melt flow rate decreased (15). These improvements in ductility and strength with increasing molecular weight are ascribed to to increases in the concentration of tie molecules (9) (10) (13). The changes with bulk PE materials are mirrored in the behaviour of the joint. Increasing the fusion times, and thus also the fusion temperature, raises joint strength (see Figs. 2, 3 and 4), significantly increases the 80°C stress rupture lifetime (Fig 5) and elliminates brittle failures by changing the failure plane to through the wires. We propose these improvements in joint strength and ductility are due to time and temperature allowing extended diffusion of the high molecular weight species across the joint, with these molecules being pinned, on cooling, at either side of the joint.

Joint Degradation

The studies of Nishimura and his co-workers (4) (5) clearly demonstrate the strength of simulated E/F joints declines if the fusion time is too long, see Figs. 4 and 5. PE resins for pipe applications are thermally well stabilised, but time at elevated temperature can lead to a consumption of the stabilizer and ultimately to a loss of molecular weight (4) (16). Once the molecular weight begins to decline the material strength declines rapidly, with the failure mode changing from ductile to brittle.

With E/F joints, too long a fusion time keeps the resin at the joint at temperature for too long a period of time. The allowed time at temperature cannot be uniquely defined, since it is temperature dependent. But once this time is exceeded, the PE resin immediately around the resistance heating wires degrades with a loss of molecular weight and thus toughness. With well designed PE pipe couplers joint degradation is never seen in practice, provided the correct fusion time is used. This phase of the joining process is thus not considered any further.

Joint Cooling

With presently available commercial E/F fittings a current is caused to flow to give energy to the joint. Once the current ceases to flow the energy input to the joint stops and the cooling phase starts. With E/F joining there is no forced cooling, so the cooling rate is relatively slow. Resin crystallization starts remote from the resistance heating wires and adjacent to the cold cage, areas where the body of the fitting and the pipe bore region act as heat sinks. As cooling and crystallization proceeds in towards the resistance heating wires, the PE contracts. To allow for this contraction, and the polymer used to fill the initial gap between the pipe and fitting (see Fig. 6 (a)), geometry changes occur at the joint by movement of the pipe (and to a lesser extent of the coupler) inwards towards the fusion zone, see Fig. 6 (d). These inward movements are positive signs of joint formation.

In cooling, polymer from the coupler and pipe crystallize to form the joint. It is proposed that macromolecular diffusion across the interface assists in creating a strong joint. Having diffused across the joint the macromolecules must be tied each side of the joint by chain entanglements in the amorphous phase or by incorporation in crystalline lamellae. To allow these cooling events to occur, it is vital to clamp the joint securely during heating and cooling, and ensure the cooling goes to completion. At the end of the cooling phase joint ductility and strength are created by locking, at each side of the joint, the joint bridging tie molecules. The requirements for forming strong E/F joints are thus to encourage a high concentration of high molecular weight, joint bridging tie molecules, and lock such molecuoles into place by securing the joint during the cooling phase. This can only be achieved by ensuring the joint remains stable by correct use of pipe clamps.

CONCLUSIONS

The literature describing the influence of fusion time on the strength of E/F joints has been reviewed. This has revealed that the fusion joining process can be divided into the following phases; incubation period, joint formation stage, joint consolidation phase (followed by joint degradation if the fusion time is too long) and finally joint cooling. This division of the fusion process into the various phases is based on measuring joint strength by four different procedures. On a molecular level it is proposed that diffusion contributes significantly to the development of strength and ductility in E/F joints. Strong joints with good resistance to brittle failure are promoted by high molecular weight polymer diffusing to bridge the joint. When strong E/F joints are formed they can join a wide range of PE resins giving joints that have strengths comparable to that seen for pipes.

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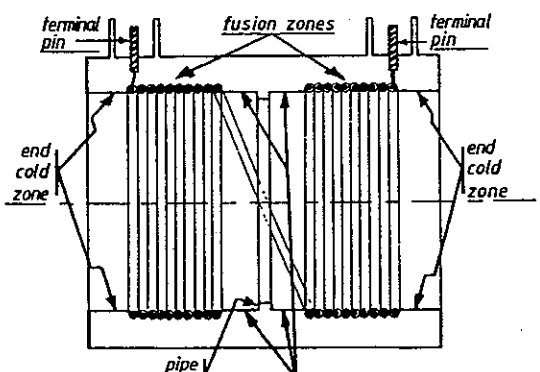

FIGURE 1
SCHEMATIC REPRESENTATION OF THE DESIGN OF AN ELECTROFUSION COUPLER.

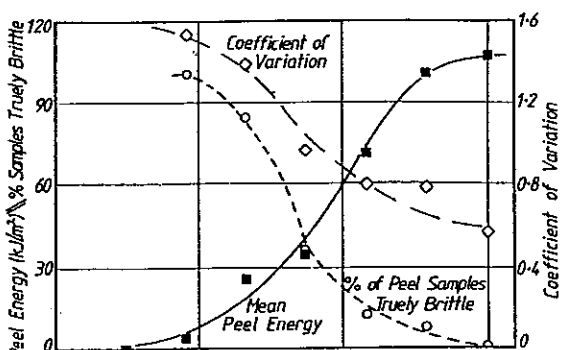

FIGURE 3(b)
FOR A 180mm COUPLER FUSED AT MINIMUM POWER AT −5°C. THE INFLUENCE OF FUSION TIME ON MEAN PEEL ENERGY, COEFFICIENT OF VARIATION AND % OF SAMPLES BRITTLE.

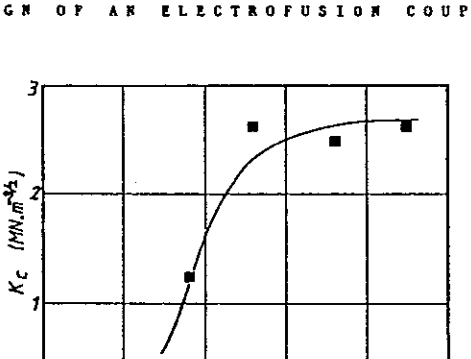

FIGURE 2
MEASURED FRACTURE TOUGHNESS (Kc) AS A FUNCTION OF FUSION TIME FOR SAMPLES CUT FROM AN ELECTROFUSION JOINT.

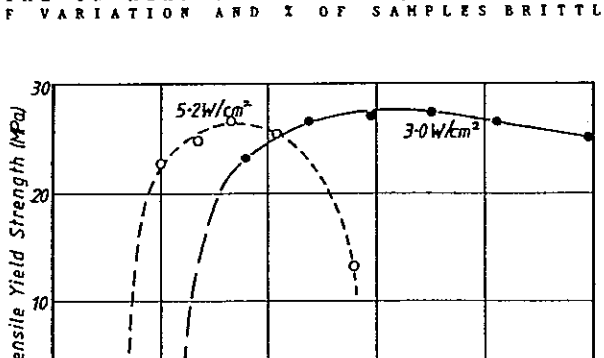

FIGURE 4
THE EFFECT OF FUSION TIME ON TENSILE YIELD STRESS OF SAMPLES CUT FROM SIMULATED ELECTROFUSION JOINTS FORMED AT TWO RATES OF ENERGY INPUT

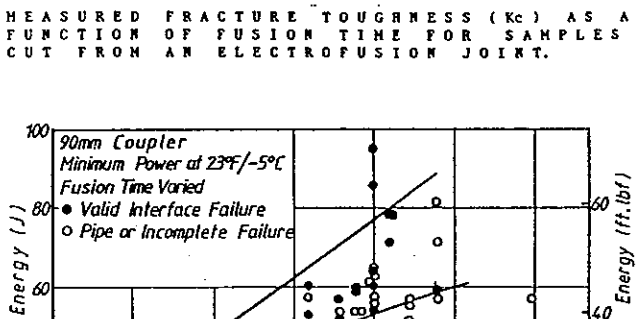

FIGURE 3(a)
MEASURED PEEL ENERGY AS A FUNCTION OF FUSION TIME. EACH DATA POINT IS THE RESULT FROM A SINGLE PEEL TEST.

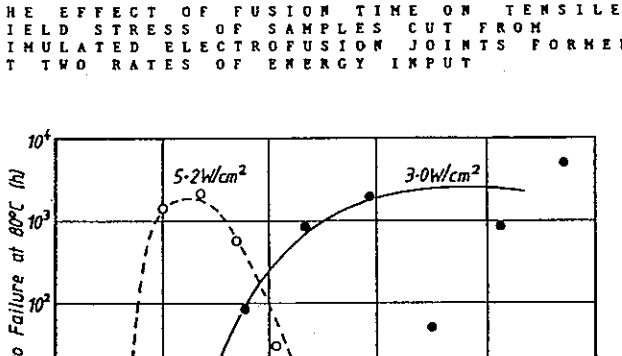

FIGURE 5
FOR AN APPLIED STRESS OF 3.9 MPa THE 80°C LIFETIME OF NOTCHED SAMPLES CUT FROM SIMULATED ELECTROFUSION JOINTS.

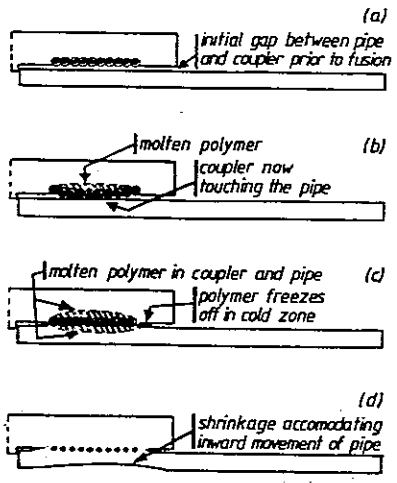

FIGURE 6

STAGES IN THE FORMATION OF JOINTS;
(a) INITIAL GAP PRIOR TO FUSION
(b) AT THE END OF THE INCUBATION PHASE
(c) JOINT CONSOLIDATION, WITH MELT POOL
(d) FORMED AND COOLED JOINT.