NRC Publications Archive
Archives des publications du CNRC

Innovative approach to testing the quality of fusion joints

Daigle, L.; Zhao, J. Q.; Beaulieu, D.

This publication could be one of several versions: author’s original, accepted manuscript or the publisher’s version. / La version de cette publication peut être l’une des suivantes : la version prépublication de l’auteur, la version acceptée du manuscrit ou la version de l’éditeur.
For the publisher’s version, please access the DOI link below./ Pour consulter la version de l’éditeur, utilisez le lien DOI ci-dessous.

Publisher’s version / Version de l'éditeur:
https://doi.org/10.1179/146580103225004153
Plastics, Rubber and Composites, 32, October, pp. 385-395, 2003-10-01

NRC Publications Record / Notice d'Archives des publications de CNRC:
https://nrc-publications.canada.ca/eng/view/object/?id=9e7ec947-80a5-4d1c-9c43-67001b9cebef
https://publications-cnrc.canada.ca/fra/voir/objet/?id=9e7ec947-80a5-4d1c-9c43-67001b9cebef

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

Innovative approach to testing the quality of fusion joints

Daigle, L.; Zhao, J.Q.; Beaulieu, D.

NRCC-46267

A version of this document is published in / Une version de ce document se trouve dans :
Plastics, Rubber and Composites, v. 32,no. 8/9, Oct. 2003, pp. 385-395.
doi:10.1179/146580103225004153

Innovative Approach to Testing the Quality of Fusion Joints

Lyne Daigle[1], M.Sc., P.Eng.
Technical Officer
Institute for Research in Construction, National Research Council Canada
M-20, Montreal Road, Ottawa, ON K1A 0R6
Phone: (613) 998 – 2584 Fax: (613) 954 – 5984 Email: lyne.daigle@nrc_cnrc.gc.ca

Jack Q. Zhao, Ph.D., P.Eng.
Senior Structural Project Manager
City of Ottawa
Transportation, Utilities and Public Works
3rd Floor, 560 Rochester Street, Ottawa, ON K1S 5K2
Phone: (613) 580-2424 Fax: (613) 560-6079 Email: jackq.zhao@ottawa.ca

Denis Beaulieu, Ph.D., P.Eng.
Professor
Civil Engineering Dept., Laval University, Québec G1K 7P4
Phone: (418) 656 – 2869 Fax: (418) 656 – 2928 Email: denis.beaulieu@gci.ulaval.ca

---

[1] Corrresponding author

Abstract

The exterior beads formed during a butt fusion process were used for non-destructive testing of the quality of butt-fused HDPE pipe joints. This innovative concept was tested using a dimensionless quality parameter that is based on tensile energy to break (TEB) values obtained from tensile testing of both the bead and joint specimens. The results show an r^2 of 0.87 for a linear regression between these two sets of specimens, which supports the hypothesis that the external bead squeezed out of a butt-fused joint can be used to test the quality of the joint itself. Statistical analysis was carried out to determine the effects of other tested parameters. Furthermore, four distinct failure modes have been identified and a quality test protocol using the quality parameter is proposed.

Key words: butt fusion, joint quality, HDPE pipe, nondestructive testing, dust contamination

Background

Butt fusion is a method commonly used to join polyethylene (PE) pipe sections together to form long installation lengths for the construction or rehabilitation of buried infrastructure such as watermains, sewers and gas pipelines. In the fusion joining process, the welding surfaces of two pipe segments are properly trimmed and prepared. Then, the fusion process consists of four sequential steps: heating, heat soaking, heater plate removal and joining-cooling (Plastics Pipe Institute 1993; Potente et al. 1988; ASTM D 2657-97 1997). Recommended procedures for butt fusion have been established (Barber and Atkinson 1974; Plastics Pipe Institute 1993; Benkreira et al. 1991a; 1991b). If fusion joints are made following the recommended procedures and in ideal environmental conditions, the joints will have mechanical properties approximately as good as the parent pipe material (Bowman 1996; Munns and Georgiou 1999; Plastics Pipe Institute 1993). This, however, also implies the dependency of fusion joint quality on the environmental conditions and the welding procedures followed at the time of fusion joining. It has been realised that improperly-made butt fused joints may be the weakest links in the pipelines (Cowley and Wylde 1978; Girardi 1992; Lu et al. 1992).

Construction sites are not always ideal environments for fusion joining and the recommended joining procedures may not be always followed. Wind and other external factors may introduce contaminants such as dust, soil, water and grease to the welding surfaces of the pipe, as well as to the surfaces of the heater plate (Marshall 1991). Dust deposits inside the pipe near the pipe ends may be attracted to the welding surfaces because of electrostatic potentials created by the rotating motion of the trimming plate during the preparation of the welding surfaces. Removal of dust contamination on welding surfaces is critical and needs to be considered in fusion processes (Marshall et al. 1995). Marshall (1991) finds that dust contamination can cause fusion joints in thick-walled pipes to be more susceptible to brittle failure. Cooling and oxidation on the melt surfaces can lead to defective cold joints (Benkreira et al. 1991a). In addition, water pipes are subjected to internal cyclic loading due to diurnal water demand and closing/opening of the valves in the water system (Bowman 1990; Zhao and Daigle 2002). The study by Cowley and Wylde (1978) shows that premature failure at butt fusion joints in polyethylene pipe systems can occur under fatigue loading. Barker and Bevis (1983) show in another study that the service life of the tested polyethylene pipe was dependent on the size of the fracture-initiating inclusions in the pipe wall. The larger the size of the inclusions, the shorter the service life.

In order to ensure the desired quality of fusion joints and to achieve the same level of service life as the parent pipe, field quality assurance/quality control (QA/QC) must be performed on the fused joints. Current practice in field quality control on butt-fused joints is limited to the visual examination of the joint (Hinchcliff and Troughton 1998; Pimputkar 1989; Marshall 1991; Kimata et al. 1987). Destructive quality testing, which involves cutting samples across a pipe joint, is also used to determine the quality of fusion joints under the specific condition (Hinchcliff and Troughton 1998; DeCourcy and Atkinson 1977; Marshall 1991; WIS 4-32-08 1994), assuming all other joints are made the same way. Burst testing of a certain pipe length is also used (Bowman 1996) but this type of destructive testing only provides an indication of the global joint performance (i.e., weakest link). Ultrasonic and radiographic techniques for non-destructive evaluation of joint quality, though promising, are yet to be fully developed (Munns and Georgiou 1999) and when they are commercially available they may be cost-prohibitive for extensive use on job sites. Reynolds et al. (1998) employed the so-called "External Bead Test" in their study on joint quality. The test, which involves removing the bead, and bending and twisting it to visually identify joint slits or weak points, is qualitative at the best. Using the height and shape of external beads as a quality indicator has also been suggested (Reynolds et al. 1998; Folkes et al. 1991; Hinchcliff and Troughton 1998; Kimata et al. 1987). Bead geometry is affected by joining parameters such as melt depth (a function of heating time, heating temperature and wall thickness) and joining pressure (Pimputkar 1989; Potente and Tappe 1988). Mathematical models have been developed to determine the joint strength based on the geometry. Those models, however, do not currently include any consideration for the effect of joint contaminants.

This paper presents an innovative concept - to test specimens taken from the bead formed on the exterior surface of a fusion joint for determining the quality of the joint. This method, though destructive to the tested bead specimens, is non-destructive to the fusion joint. The concept and corresponding experimental tests are described.

Hypothesis and Theory

It is hypothesized that the bond strength across the joining plane in the pipe wall correlates proportionally to that of the joining plane in the beads. In other words, if dust contamination or inadequate heating temperature affects the quality of a fusion joint, it will equally affect the quality of the joint in the bead that is formed on the exterior (and interior) surface. The objective of this study is to test this hypothesis and to determine the degree of correlation.

The theory behind this hypothesis is that when two molten pipe ends are brought together under a given pressure, some molten material will be forced to flow out of the pipe wall. Some will flow towards the pipe's exterior surface and some towards the pipe's interior surface. That is, there is a point in the joining plane that separates the flows into two opposite directions (Fig. 1). As a result, the material at this separation point will theoretically have zero displacement, and materials at other points along the joining plane will be displaced in proportion to their distance from the separation point. The further away from the separation point, the more displacement it will experience. If there is dust contamination on the molten pipe ends, some dust particles will be displaced into the beads while others will remain at the joining plane. The resulting dust concentration will be reduced due to the stretching of the joining plane.

Experimental Work

Test joints

Test fusion joints were made on a 455 mm (18 in.) outside diameter high density polyethylene (HDPE) pipe. The pipe was manufactured with PE 3408 resin and had a standard diameter ratio (SDR) of 21. The test joints were made by an experienced operator using a commercial butt fusion machine inside a workshop. Conditions that were created during the fusion joining included combinations of two dust types and three wind velocities. A set of control joints were also made for comparison. The dusts were dry clay and cement powder, both are common materials found on a job site. Wind was created with a table fan to simulate three possible on-site conditions. Details on dust particles and creation of dusty condition are given elsewhere (Zhao et al. 2002).

Under each combination of the parameters, three joints (joints A, B and C) were made at a distance of 455 mm (18") apart, with joint A being closest to the fan location. A total of 21 test joints were made (Table 1). Heating time, removal time, joining and cooling time and joining pressure were left to the discretion and judgment of the operator. The joining pressure was 2.1 MPa (307 psi) for the first 2-3 minutes of the joining-cooling process and then was reduced to 0.2 MPa (30 psi) for the remaining joining-cooling time. The temperature of the heater plate, measured with a portable laser thermometer, was observed to vary about 10 ºC across the plate surface, the warmer location being at the bottom of the plate (Zhao et al. 2002).

Preparation of test specimens from joint and bead

A sample from each test joint was cut at the invert (the bottom position on the pipe's circumference) where the dust accumulation was observed to be the most. The sample was then made into two dog-bone shaped test specimens (a total of 42), which were designed to include as much as possible the pipe wall thickness (Fig. 2a). The width to thickness ratio was 2.5:1 over the gauge length, which was within the dimensions for tensile test specimens as per ASTM D 638-99 (1999). These specimens were machined specifically to have the fused joint in the middle of the gauge length.

Bead test specimens were made from the samples taken at the corresponding joint sample locations. The exterior beads were cut carefully flush at the pipe surface. Bead slices of 1 mm (1/25") thick were then sectioned using a microtome. Subsequently, small dog-bone specimens were prepared out of these bead slices (Fig. 2b). These dog-bone specimens were examined under a microscope and the ones that had visible cracks were discarded. These cracks were not created by bad joints, rather during the preparation of the small specimens. Five to ten bead specimens (a total of 152) were made that corresponded to the location of the joint specimen.

Large and small dog-bone specimens from the pipe wall (away from the joints) were also prepared and tested for comparison.

Tensile tests

All specimens, large and small, were tested under short-term tensile loading using the same test procedure on an Instron machine (Model 4500-4502). All tests were carried out in a laboratory where the relative humidity was maintained between 45% and 55% and the room temperature between 21 ºC and 25 ºC. For the small bead specimens, the crosshead speed was chosen to be 0.5 mm/min. (1/48 inch per minute). At such a speed, plastic deformation would start in about eight minutes. When elongation reached 100%, the crosshead speed was changed to 2 mm/min. (1/12 inch per minute) for the rest of the test until failure of the specimen. For the large joint specimens, the crosshead speed was set at 3 mm/min. (1/8 inch per minute) in order to obtain the same strain rate as the bead specimens. The crosshead speed was changed to 12 mm/min. (1/2 inch per minute) when 100% elongation was reached.

No existing standards could be followed in the tensile testing of the bead specimens due to their unique size and geometry. Nevertheless, every effort was made to have comparable conditions between the joint and the bead specimens and whenever possible, ASTM D 638-99 (1999) and D 882-97 (1997) were followed. It is the comparison of the two sets of specimens that is of ultimate importance in this study.

Microscopic examinations

In order to visualize the presence of dust particles on the joining plane and to understand the failure mechanism of contaminated joints, the joint and bead specimens that broke at the weld in a brittle manner were examined under an optical microscope.

Results and discussion

Observed dust accumulation on welding surfaces

To inspect the welding surfaces for dust contamination during a fusion process is simply not possible because of the short removal time. Instead, a qualitative test was carried out for this purpose prior to the heating of the pipe ends. In this test, the trimmed pipe ends were brought to within approximately 150 mm (6”) of each other, a typical gap during the removal of the heater plate. The dust was then blown into the pipe for 5 seconds, a typical removal time, followed by a visual examination. Fig. 3 shows a welding surface heavily contaminated with dust. Non-uniform dust distribution was observed across the pipe wall thickness and along the circumference of the pipe. More dust accumulated near the invert than at any other circumferential location, and more dust on the inner section of the pipe wall thickness than on the outer section.

Fracture surfaces of contaminated joints

Microscopic examination of the fracture surfaces was possible for the specimens that broke in a brittle manner. Fig. 4a is a picture of the magnified fracture surface of the joint specimen from Joint 4C that was contaminated with cement dust. Fig. 4b is the fracture surface of the bead specimen taken from the same joint. Note that on the bead fracture surface, the final breaking area of the bead specimen was the necked cross-sectional area, which is smaller than the original cross-sectional area in the background. The term "necked" refers to the phenomenon of the reduced cross-sectional area of a test specimen while it undergoes plastic elongation under tensile testing. Cement particles are seen as white dots on the fracture surfaces, and some voids are also evident. Similar features are seen on the fracture surfaces of the joint contaminated with clay dust (joint and bead specimens in Fig. 5a and 5b, respectively).

These results show that the dust particles are not completely squeezed out of the joints during fusion process. Marshall (1991) reaches the same conclusion in his study using dust transferred from the heater plate onto the molten pipe ends. These observations support the theory postulated above, on which the hypothesis is based.

Furthermore, voids present on the fracture surfaces of the contaminated joints suggest that the trapped dust particles may have acted as void and later as crack initiating points when the pipe was subjected to loading. Long-term fatigue loading, such as the diurnal cyclic pressures in watermains, may cause initiation of cracks from the trapped dust particles. In addition, the trapped dust particles may act as a barrier to the mixing of the molten materials from both pipe ends, thus creating a weaker plane (Barber and Atkinson 1974; Bowman 1996; Marshall 1991).

Failure modes

The effect of dust contamination is evidenced by different failure modes observed during the tensile testing. Furthermore, similar failure modes are observed for both bead and joint specimens. The failure modes for joint specimens are described by Zhao et al. (2002). For bead specimens, the basic failure modes remain the same but elongation limits are higher than those for the joint specimens. Thinner bead specimens, in general, have a larger elongation than their joint counterparts. This behavior of the polyethylene material has been recognized (Wilson 1995; Marshall 1991). These failure modes of the bead specimens are given below:

> **Mode 1** – The specimen broke at the fusion weld before necking started. Failure was brittle and the maximum strain was less than 100%. This type of failure mode is considered to be produced by a "bad" joint in the bead.
>
> **Mode 2** – The specimen passed the yield point, followed by necking that continued past the fusion weld. Failure occurred at the weld before the gauge length was fully necked. The maximum strain varied between 100% and 500%. This type of failure mode is considered to be produced by a "poor" joint in the bead.
>
> **Mode 3** – The gauge length of specimen was completely necked when failure occurred at the weld. The maximum strain varied between 500% and 1000%. Bead specimens that fail in this mode are considered to have a "good" joint.

> **Mode 4** – The gauge length of specimen was completely necked when failure occurred away from the weld. The maximum strain was above 1000%. This magnitude of maximum strain is comparable to that of the parent pipe. Bead specimens that fail in this mode are considered to have an "excellent" joint.

Fig. 6 shows the physical shapes and appearances of these modes of failure and Fig. 7 shows the stress-strain representations of these modes. It is noted that behavior of a specimen depends heavily on its geometry and, therefore, the above failure modes and the quality criterion are only applicable to bead specimens of the same geometry as tested in this study.

Comparison of joining quality of joint and bead specimens

Table 2 shows a comparison of yield stresses and tensile energy to break (TEB) values of both the joint and bead specimens. The values shown are averages of all test specimens under each condition. The yield stress is defined as the first peak value in the stress-strain curve beyond which the specimen undergoes plastic deformation (Fig. 7). The tensile energy to break (TEB) is the area under the stress-strain curve, i.e.:

$$TEB = \int \sigma d\varepsilon \tag{1}$$

where σ is the stress and ε the strain.

The yield stresses of the bead specimens vary from 16.9 to 18.2 MPa, which is within ±4% of the mean value of 17.5 MPa. The yield stresses of the joint specimens vary from 21.1 to 22.3 MPa, within ±3% of the mean value of 21.7 MPa. These small variations in yield stresses indicate that although different failure modes were observed, the dust contamination on the welding surfaces had little effect on the yield stress. The yield stresses of the bead specimens are in general smaller than those of the joint specimens. The same is seen for the yield stresses of the bead-size and joint-size pipe wall specimens. The mean yield stress of the bead-size pipe wall specimens is 17.7 MPa, whereas that of the joint-size pipe wall specimens is 21.2 MPa, a 20% difference. This observation suggests that the yield stress of HDPE pipe decreases with the decrease in specimen thickness, a phenomenon also observed by Wilson (1995). In contrast, the TEB value (0.224 J/mm^3) of the bead-size pipe wall specimens is 70% higher than that (0.132 J/mm^3) of the joint-size pipe wall specimens, also due to the effect of specimen thickness. Thin specimens of polyethylene elongate more, thus have higher TEB values, than thick specimens of the same material (Wilson 1995; Marshall 1991). Therefore, it is important that the specimens of the same dimensions be used in implementing a field quality test protocol.

The TEB values of both joint and bead specimens vary from 0.01 to 0.15 J/mm^3 (Table 2). This wide range of variations was then analyzed for correlation. Although TEB values can be used directly, a dimensionless quality parameter (Ψ) that is based on TEB and the mean yield stress and strain of the pipe wall specimens, is proposed as:

$$\Psi = \frac{TEB}{\sigma_{y,wall}\varepsilon_{y,wall}} \tag{2}$$

where $\sigma_{y,wall}$ is the mean yield stress and $\varepsilon_{y,wall}$ the mean yield strain of the pipe wall specimens. For each of the bead and joint data sets, the mean yield stress and strain are constant. Therefore, the use of this new quality parameter does not change the degree of correlation.

Ψ-values of the bead specimens and those of the joint specimens were calculated using Equation 2 and compared with each other. A linear regression shows that a relationship between the two sets of data is evident ($r^2 = 0.709$) (Fig. 8). A further analysis shows that a better correlation ($r^2 = 0.871$) exists between the Ψ-values of the bead specimens and those of the outer wall joint specimens (Fig. 9). This better correlation is due to the fact that the bead specimens were all taken from the beads formed on the pipe's exterior surface. Materials for the external bead come from the zone between the flow separation point and the exterior surface within the pipe wall. (No attempts were made to test the specimens from the internal beads because of little practical implications.)

Although the sample population is by no means large, the results of this experimental study have shown a convincing correlation between the quality of the bead specimens and the quality of the joint specimens. This finding supports the hypothesis that the external bead formed during a joint fusion process can be used to determine the quality of the fusion joint itself. The scatter of data suggests that it is necessary to test a sufficient number of bead specimens in order to obtain representative mean values.

A number of statistical tests were carried out to determine the degree of influence of the tested parameters (Table 3). Significance is judged at the 95% confidence level. The difference in the quality of the control and contaminated joints of both the bead and joint specimens is significant. This further confirms that dust contamination on the welding surfaces of HDPE pipe affects the joint quality of both beads and joints. *F*-tests show that the cement dust has a significantly more adverse effect that the clay dust for the bead, but the same level of effect as the clay dust for the joint specimens. The failure mechanism of bead and joint specimens contaminated with clay and cement dust remains the subject of further study.

The effect of different wind velocities is not significant statistically. In other words, the three wind velocities used in the experiment produced similar contamination on the molten pipe ends. This suggests that the experiment could be improved by using a larger range of wind velocities and dust intensities, in order to determine at what velocity the effect of dust becomes negligible.

An interesting observation is that the difference in quality between the control and pipe wall specimens is significant for the bead specimens, but not for the joint specimens. On one hand, this suggests that the beads, which formed without confining pressures, are low in quality even without dust contamination. On the other hand, this confirms that the properly-made fusion joints are as good as the parent pipe wall. The inner and outer wall joint specimens show no significant difference between their means even though a better correlation exists between the outer wall joint specimens and the bead specimens than between the inner wall joint specimens and the bead specimens.

Conclusions

An innovative concept for testing non-destructively the quality of butt-fused joints of HDPE pipe was formulated and tested with specimens prepared from the beads and pipe joints of butt-fused HDPE pipe segments. Statistical analysis was carried out to determine the correlation between the quality of the bead and joint specimens, as well as the effect of dust type, wind velocity, and the difference between inner and outer pipe wall specimens. Based on the results, the following conclusions can be drawn:

- The data confirmed that the quality of the butt-fused joints, if made properly, is as good as that of the parent pipe wall.

- Dust contaminants on the welding surfaces are not completely squeezed into the beads during fusion process. As a consequence, contaminated joints may fail in one of the four distinct modes of failure. A failure criterion has been established and can be used to categorize the quality of a fused joint into four grades: bad, poor, good and excellent.

- Using a newly proposed dimensionless quality parameter, the analysis shows a convincing correlation between the quality of the bead and the joint specimens. This supports the hypothesis that the bead squeezed out of a butt-fused joint can be used to test the quality of the joint itself.

- Joint contamination has little effect on the yield stress of HDPE pipe. However, the yield stress decreases with the decrease in specimen thickness. In implementing a field quality test protocol following the approach presented in this paper, it is important that the specimens of the same dimensions be used consistently.

- The quality of beads under optimum joining conditions is not as good as the parent pipe wall, possibly due to the unconfined formation of the beads on the pipe surface.

Significance of this innovative approach

This study has shown that the external bead formed on the outside of a fusion joint can be used to determine the quality of the joint, while leaving the joint intact. A mobile testing unit, employing the proposed approach, can be used to perform testing of bead specimens while the freshly-made joint cools down. Joint quality of fused HDPE pipe can then be judged based on a quality criterion such as the one shown in Table 4, thus reducing the subjectivity and inconsistency, as is the case with the current practice of visual inspection. Bad joints can thus be caught by such a screening and removed before the pipe is installed. The impact of implementing this innovative joint quality testing protocol is a better quality pipeline that will have longer service life.

Acknowledgment

This paper is a result of a research project jointly supported by the City of Ottawa, KWH Pipe (Canada) Ltd., Marcel Baril Ltée and the National Research Council Canada (NRCC). Help and comments from J. Margeson and B.B. Rajani of NRCC are greatly appreciated.

References

ASTM D 638-99. (1999). *Standard test method for tensile properties of plastics.* American Society for Testing and Materials. Philadelphia, PA, U.S.A.

ASTM D 882-97. (1997). *Standard test method for tensile properties of thin plastic sheeting.* American Society for Testing and Materials. Philadelphia, PA, U.S.A.

ASTM D 2657-97. (1997). *Standard practice for heat fusion joining of polyolefin pipe and fittings*. American Society for Testing and Materials. Philadelphia, PA, U.S.A.

Barber, P., and Atkinson, J.R. (1974). "The use of tensile tests to determine the optimum conditions for butt fusion welding certain grades of polyethylene, polybutene-1 and polypropylene pipes", *Journal of Materials Science*, **9**(9), 1456-1466.

Barker, M.B., and Bevis, J.B. (1983). "The performance and causes of failure of polyethylene pipes subjected to constant and fluctuating internal pressure loadings." *Journal of Materials Science*. 18, 1095-1118.

Benkreira, H., Shillitoe, S., and Day, A.J. (1991a)." Modelling of the butt fusion welding process", *Chemical Engineering Science*, 46(1), 135-142.

Benkreira, H., Day, A.J., and Shillitoe, S. (1991b). "Butt fusion joining of polyethylene pipes: a theoretical approach", *Proc. Int. Conf. on "Advances in Joining Plastics and Composites"*, 10-12 June 1991, Bradford, Yorkshire, UK, Martin Watson, conference technical director , organised by TWI pp. 188-201.

Bowman, J.A. (1990). "The fatigue response of polyvinyl chloride and polyethylene pipe systems." *Buried Plastic Pipe Technology, ASTM STP 1093*, American Society for Testing and Materials, 101-121.

Bowman, J. (1996). "Butt fusion joining polyethylene pipes and assessing the resultant joint strength", *Welding and Metal Fabrication*, 64(2), 62-65.

Cowley, W.E., and Wylde, L.E. (1978). "Behaviour of butt fusion welded polyethylene pipelines under fatigue loading conditions", *Chemistry and Industry*, 3(11), 371-377.

DeCourcy, D.R., and Atkinson, J.R. (1977). “The use of tensile tests to determine the optimum conditions for butt fusion welding polyethylene pipes of different melt flow index”, *Journal of Materials Science,* 8(12), 1535-1551.

Folkes, M.J., Huanton, J., and Bowman, J. (1991). “Microstructure development and its effect on the mechanical properties of butt fusion joints”, *Proc. Int. Conf. on “Advances in Joining Plastics and Composites”*, 10-12 June 1991, Bradford, Yorkshire, UK, Martin Watson, conference technical director , organised by TWI, pp. 118-127.

Girardi, M.A. (1992). “The evaluation of mechanical testing techniques and the influence of defects in MDPE butt fusion welds”, *Proc.* 8th *Int. Conf. on ”Plastic Pipe*s”, 21-24 September 1992, Koningshof, The Netherlands, The Plastics and Rubber Institute, pp. B2/6 – 1 to B2/6 – 8.

Hinchcliff, F. A., and Troughton, M. J. (1998). “Comparison of short-term coupon tests for assessing the performance of butt fusion welds in polyethylene pipes”, *Proc.10th Int. Conf. on” Plastics Pipes”*, 14-17 September 1998, Göteborg, Sweden, IOM Communications pp. 555-564.

Kimata, A., Takahashi, K., Yasui, M., Arii, A., Aizawa, A., and Masaki, A. (1987). “Application of high-speed tensile test to fusion operations in the field”, Proc. *10th Plastic Fuel Gas Pipe Symposium,* 27-29 October*, 1987,* New Orleans, LA, U.S.A., American Gas Association, pp 127-140.

Lu, X., Qian, N., Brown, N., and Buczala, G. (1992). “The effect of pressure and contaminants on slow crack growth in a butt fusion in a polyethylene gas pipe”, *Journal of Applied Polymer Science*, 46(8), 1417-1427.

Marshall, J.P. (1991). “The Influence of welding parameters on the toughness of butt fusion welds in MDPE”, Proc. Int. Conf. on “*Advances in Joining Plastics and Composites”*, 10-12 June 1991, Bradford, Yorkshire, UK, Martin Watson, conference technical director , organised by TWI pp. 202-215.

Marshall, G.P., Hepburn, D.S., Pearson, D., and Mackellar, S. (1995). “Factors affecting the toughness of electrofusion joints in PE pipe systems for the water industry”, *Progress in Rubber and Plastic Technology*, 11, 211-233.

Munns, I.J., and Georgiou, G.A.(1999). “Ultrasonic and radiographic NDT of butt fusion welded polyethylene pipes”, *Insight: Non-Destructive Testing and Condition Monitoring,* 41(5), 291-303.

Pimputkar, S.M. (1989). “The dependence of butt fusion bond strength on joining conditions for polyethylene pipe”, *Polymer Engineering and Science*, 29(19), 1387-1395.

Plastics Pipe Institute. (1993). *Polyethylene joining procedures*. The Society of the Plastics Industry, Inc., Wayne, NJ, U.S.A.

Potente, H., and Tappe, P. (1988). “Scale up laws in heated tool butt welding of semicrystalline thermoplastics”, *Welding in the World*, 26(17), 18-25.

Potente, H., Michel, P., and Tappe, P. (1988). “The principles of hot plate welding of semi-crystalline thermoplastics”, *Joining Plastics in Production*, Welding Institute, Abington, U.K. pp. 105-126.

Reynolds, N.D., Jenkins, P.W., Burgess, P., and Attwood, J. (1998). “Fast weld field trials, high productivity butt fused jointing of polyethylene pipes”, *Proc. 10th Int. Conf. on “Plastics Pipes”*, 14-17 September 1998, Göteborg, Sweden, IOM Communications, pp. 565-576.

Wilson, K.A. (1995). "Verification of butt fusion weld quality in large diameter PE100 water pipes", *Proc. 9th Int. Conf. on "Plastics Pipes"*, 18-21 September 1995, Heriot-Watt University, Edinburgh, Scotland, U.K. pp. 168-180.

WIS 4-32-08. (1994). *Specification for site fusion jointing of PE80 and PE100 pipe and fittings.* Water Industry Specification, UK Water Industry Engineering and Operations Committee, WRc plc, Bucks, U.K.

Zhao, J.Q., and Daigle, L. (2002). *Performance of HDPE Sliplined Cast Iron Watermain, Final Report*, NRCC Client Report B-5108.3, Institute for Research in Construction, National Research Council Canada, Ottawa, ON, Canada.

Zhao, J.Q., Daigle, L., and Beaulieu, D. (2002). "Effect of joint contamination on the quality of butt-fused HDPE pipe joints", *Canadian Journal of Civil Engineering,* 29(5), pp. 787-798.

Table 1. Welding parameters for butt fused joints

Condition	Joint	Heater plate temperature range (ºC)	Heating time (min.)	Heater plate removal time (sec.)	Joining-cooling time (min.)
control	2A	205-215	4	n/a	30+
	2B	210-220	4	n/a	20
	2C	205-213	3	n/a	21
Cement dust 6.4 km/h	3A	210-215	3	8	17
	3B	205-215	5	5	22
	3C	210-220	4	6	17
Cement dust 8 km/h	4A	215-220	5	5	21
	4B	210-220	3	5	30+
	4C	215-220	5	5	22
Cement dust 9.6 km/h	8A	205-210	4	5	15
	8B	205-210	4	5	18
	8C	205-215	4	5	15
Clay dust 6.4 km/h	5A	210-215	4	5	15
	5B	205-210	4	5	15
	5C	205-210	4	5	17
Clay dust 8 km/h	6A	210-215	4	5	15
	6B	205-210	4	5	30+
	6C	205-210	4	5	16
Clay dust 9.6 km/h	7A	205-215	5	5	24
	7B	210-215	4	5	26
	7C	205-215	4	5	20

n/a - not available.

Table 2. Mean yield stresses and TEB values of joint and bead specimens

Specimen location		Yield stress, MPa		TEB, J/mm^3	
		Beads	Joints	Beads	Joints
Pipe wall		17.7	21.2	0.224	0.132
2	A	18.0	21.2	0.154	0.066
(control)	B	17.8	21.6	0.133	0.141
	C	17.7	21.9	0.129	0.144
3	A	17.6	n/a	0.016	n/a
	B	17.0	21.2	0.092	0.094
	C	17.3	21.1	0.040	0.015
4	A	17.5	21.8	0.047	0.023
	B	17.5	21.5	0.011	0.018
	C	17.2	21.7	0.056	0.016
8	A	17.0	21.7	0.046	0.010
	B	17.1	22.1	0.027	0.010
	C	17.4	21.9	0.022	0.016
5	A	17.8	22.3	0.078	0.019
	B	18.2	22.2	0.097	0.096
	C	18.1	22.1	0.141	0.076
6	A	18.0	21.6	0.047	0.016
	B	17.1	22.2	0.062	0.017
	C	17.0	21.8	0.068	0.100
7	A	17.0	21.6	0.073	0.085
	B	16.9	21.1	0.047	0.017
	C	17.0	21.2	0.063	0.026

Table 3. Statistical tests (at 95% confidence level) on the effect of parameters

Parameters compared	Bead specimens	Joint specimens	Type of test
Control vs. contaminated joints	Significant	Significant	Student *t*
Cement vs. clay dusts	Significant	Not significant	*F*-test
Wind velocities	Not significant	Not significant	*F*-test
Control vs. wall specimens	Significant	Not significant	Student *t*
Inner vs. outer wall specimens	(not applicable)	Not significant	Student *t*

Table 4. Example quality criterion using quality parameter Ψ

Failure mode	Joint Quality	Range of quality parameter of joint, Ψ	Range of quality parameter of external bead, Ψ
1	bad	< 2	< 5
2	poor	2 – 10	5 – 20
3	good	10 – 18	20 – 35
4	excellent	> 18	> 35

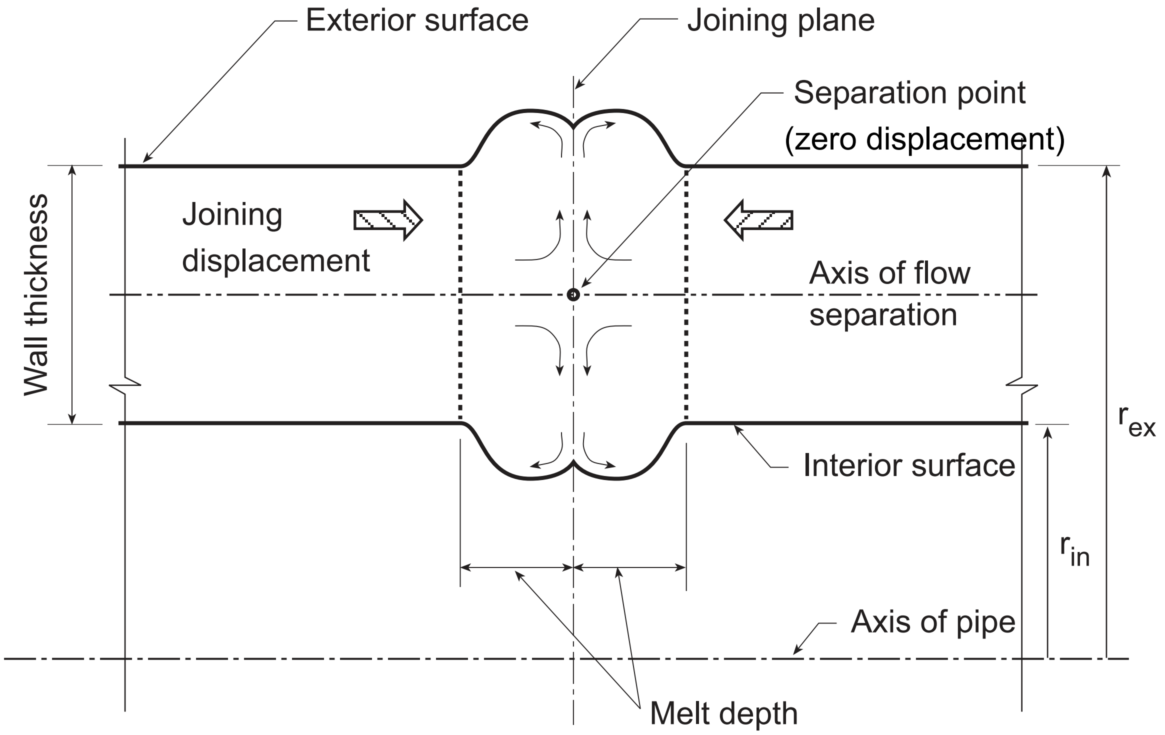
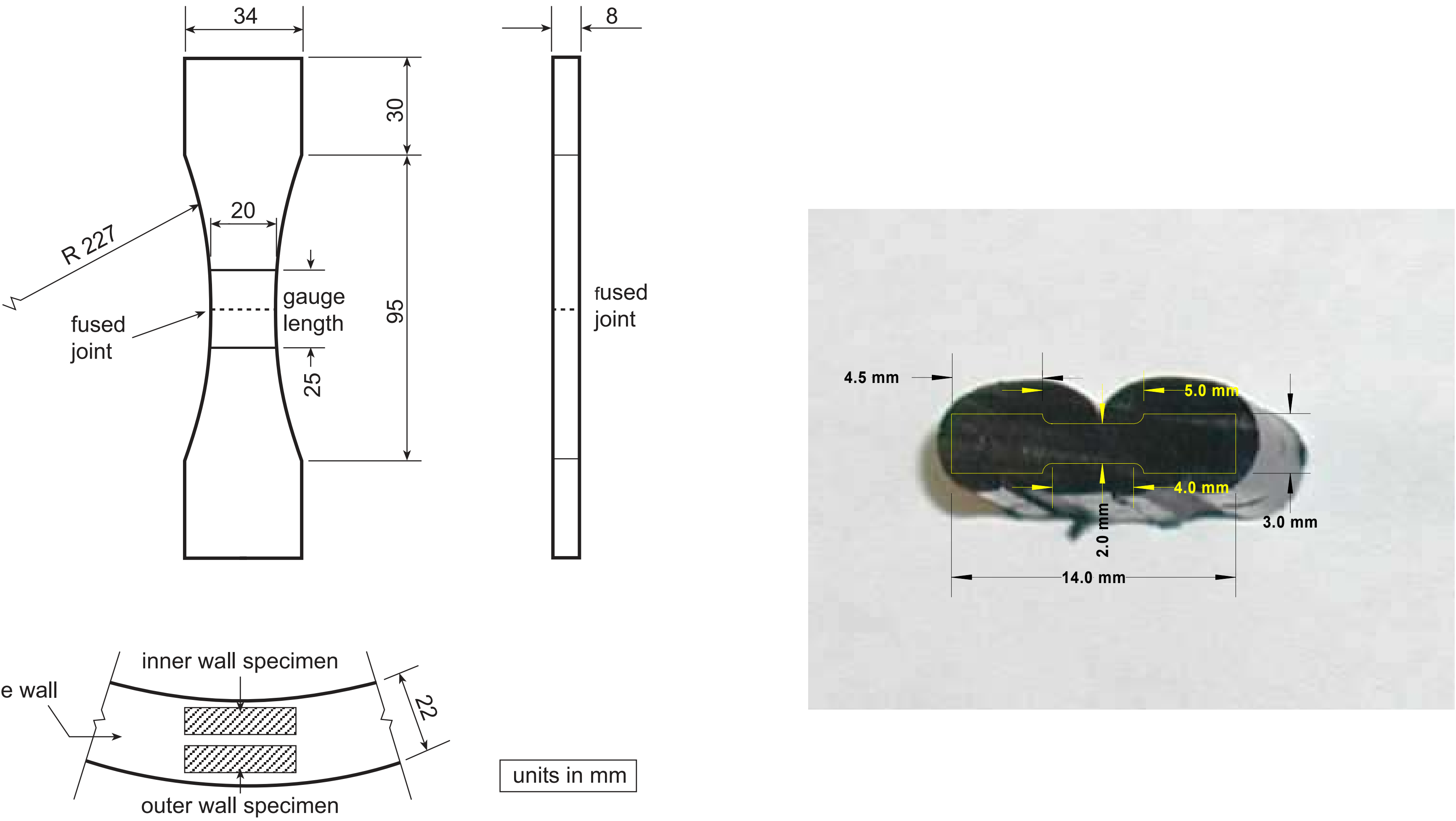


Fig. 1. Schematic representation of material flow during fusion joining (not to scale)

[**Note to internal reviewers:** The figure titles will be deleted in the final submitted version. They are kept for your ease of cross-referencing]

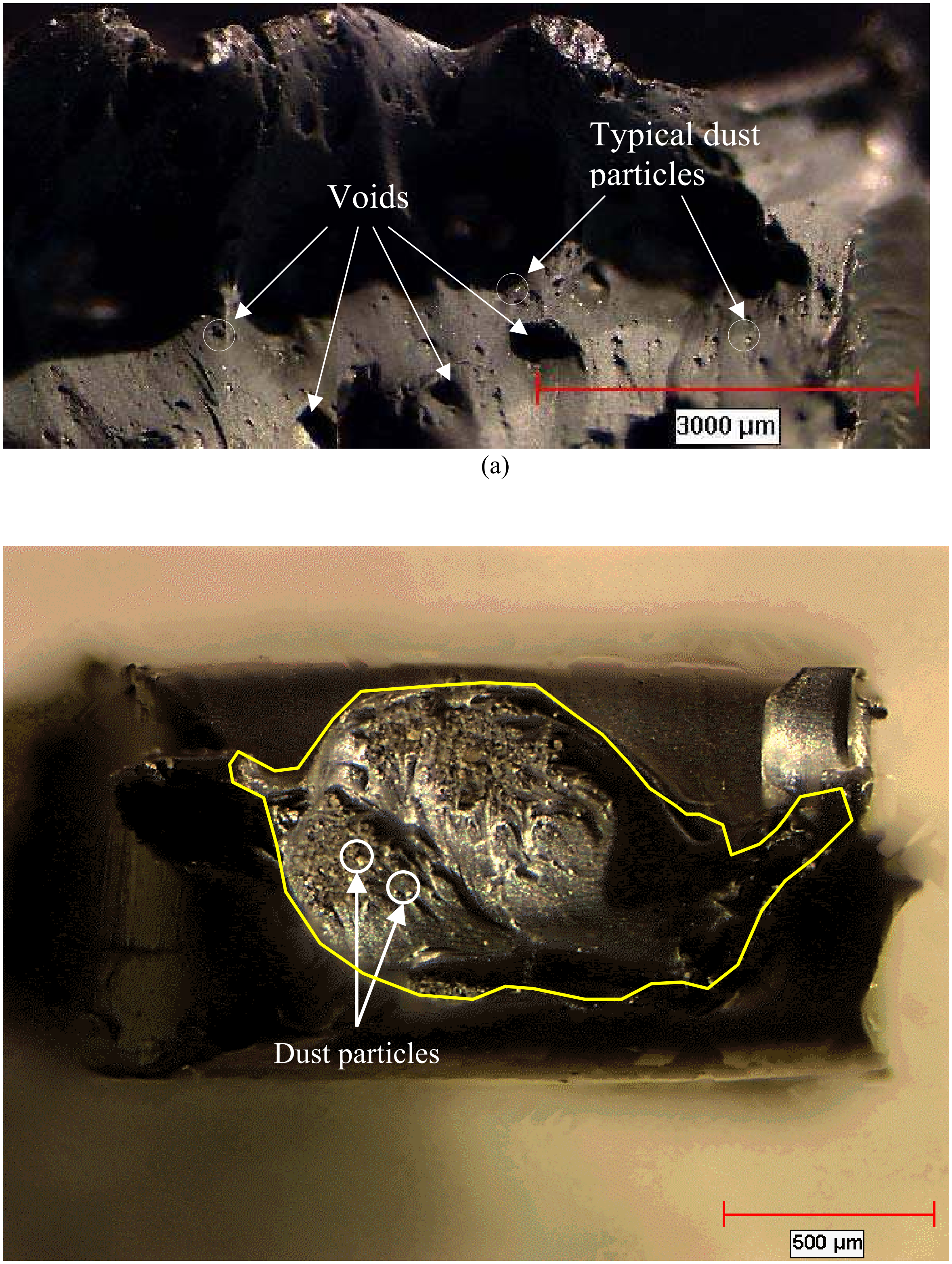


(a)

(b)

Fig. 2. Dimensions of joint (a) and bead (b) dog-bone shaped specimens

Fig. 3. Example of dust accumulation on welding surfaces after 5 seconds of dust exposure



(a)

(b)

Fig. 4. Fracture surfaces of joint (a) and bead (b) specimen from Joint 4C, showing cement dust and voids

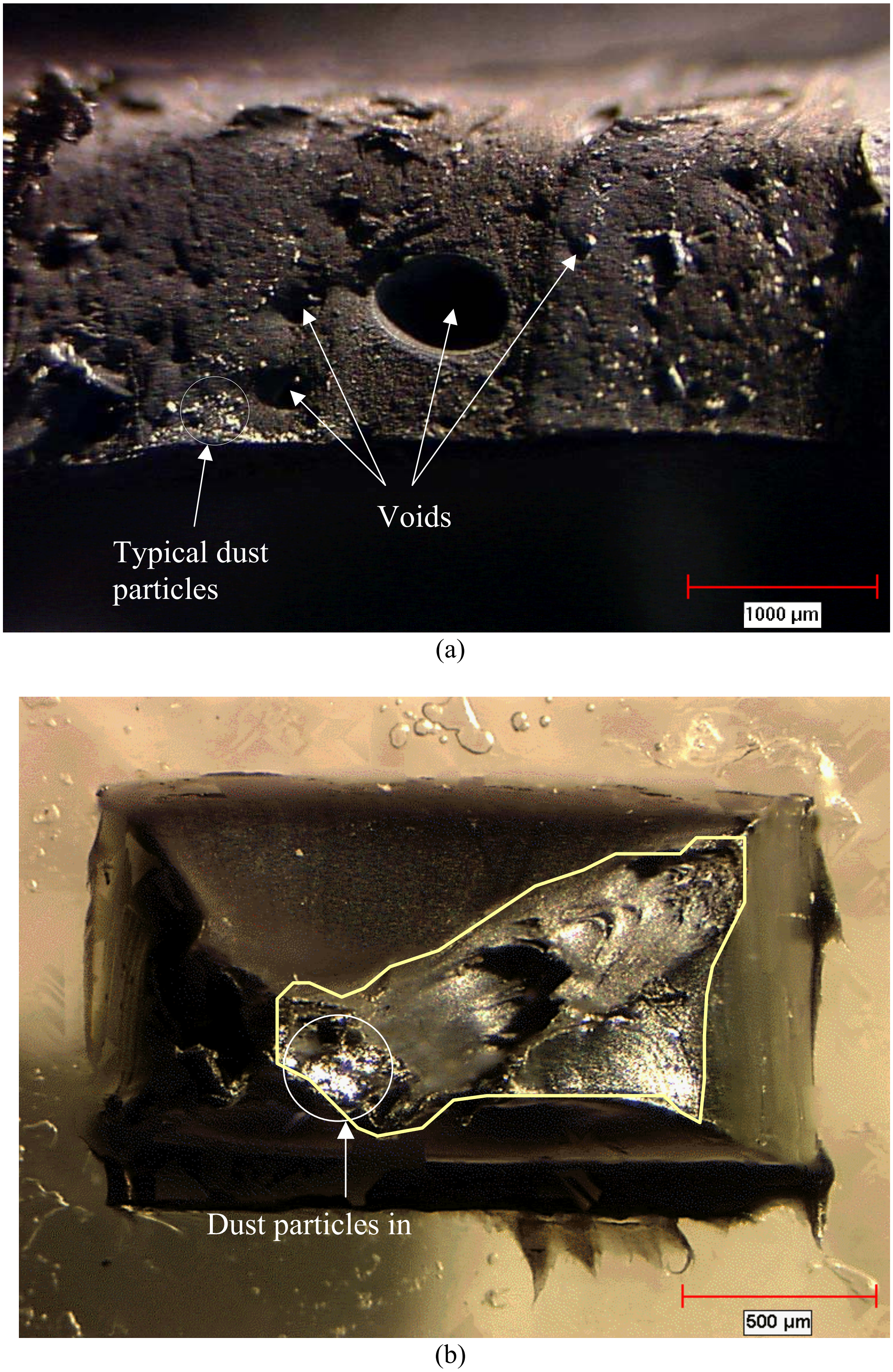
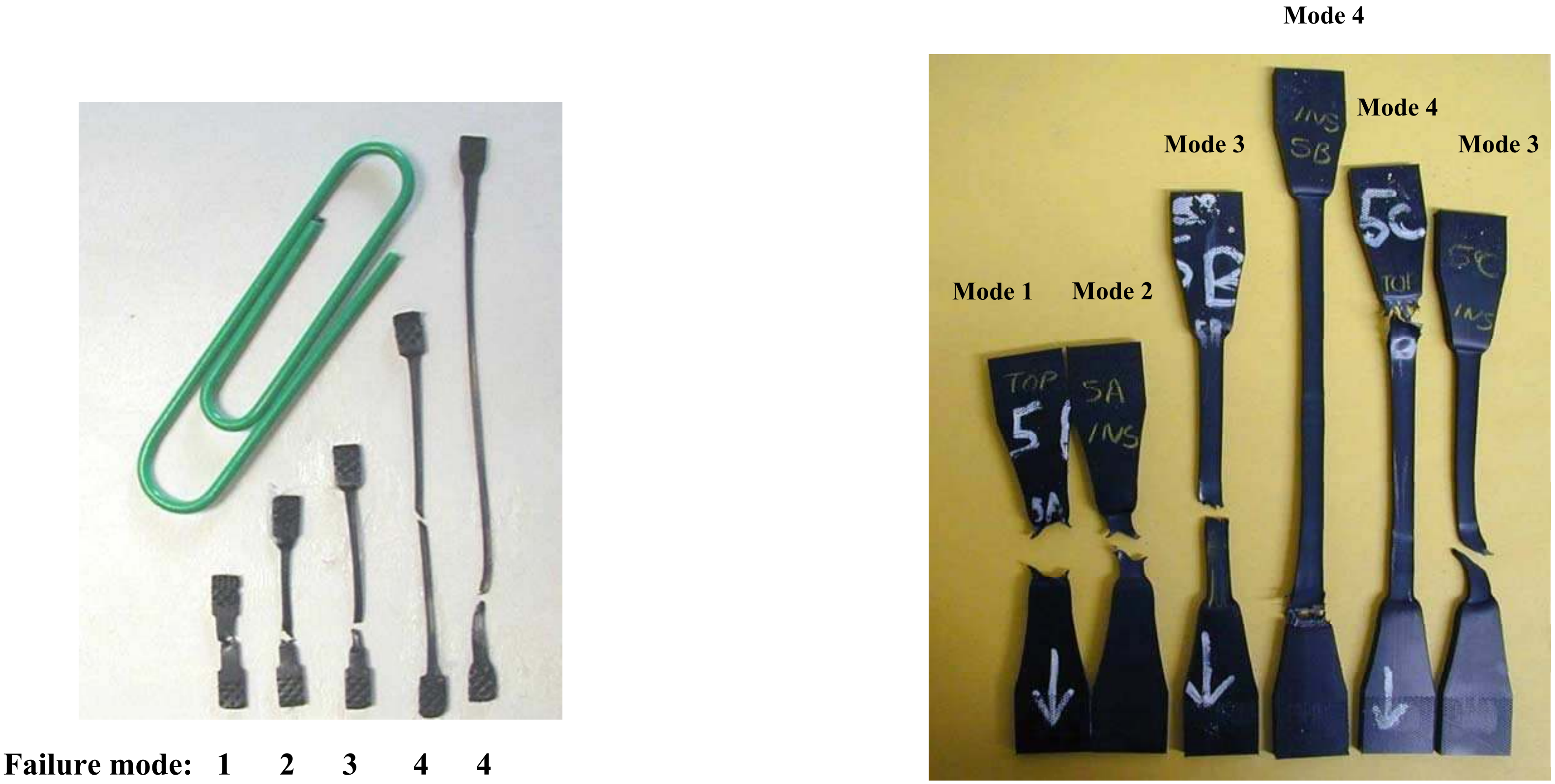


Fig. 5. Fracture surfaces of joint (a) and bead (b) specimen from Joint 7A, showing clay dust and voids



(a) (b)

Fig. 6. Failure modes of bead (a)and joint (b) specimens

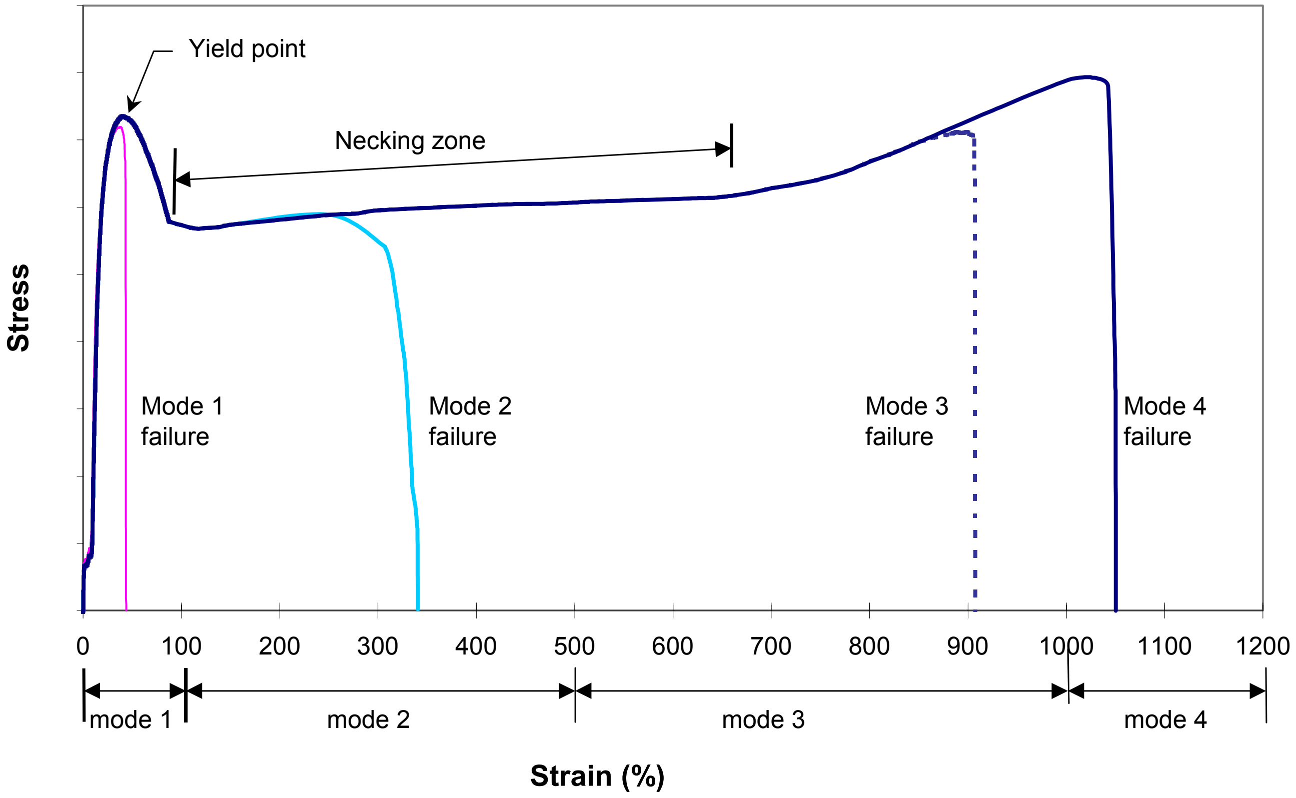


Fig. 7. Typical stress-strain curves and failure modes of bead specimens

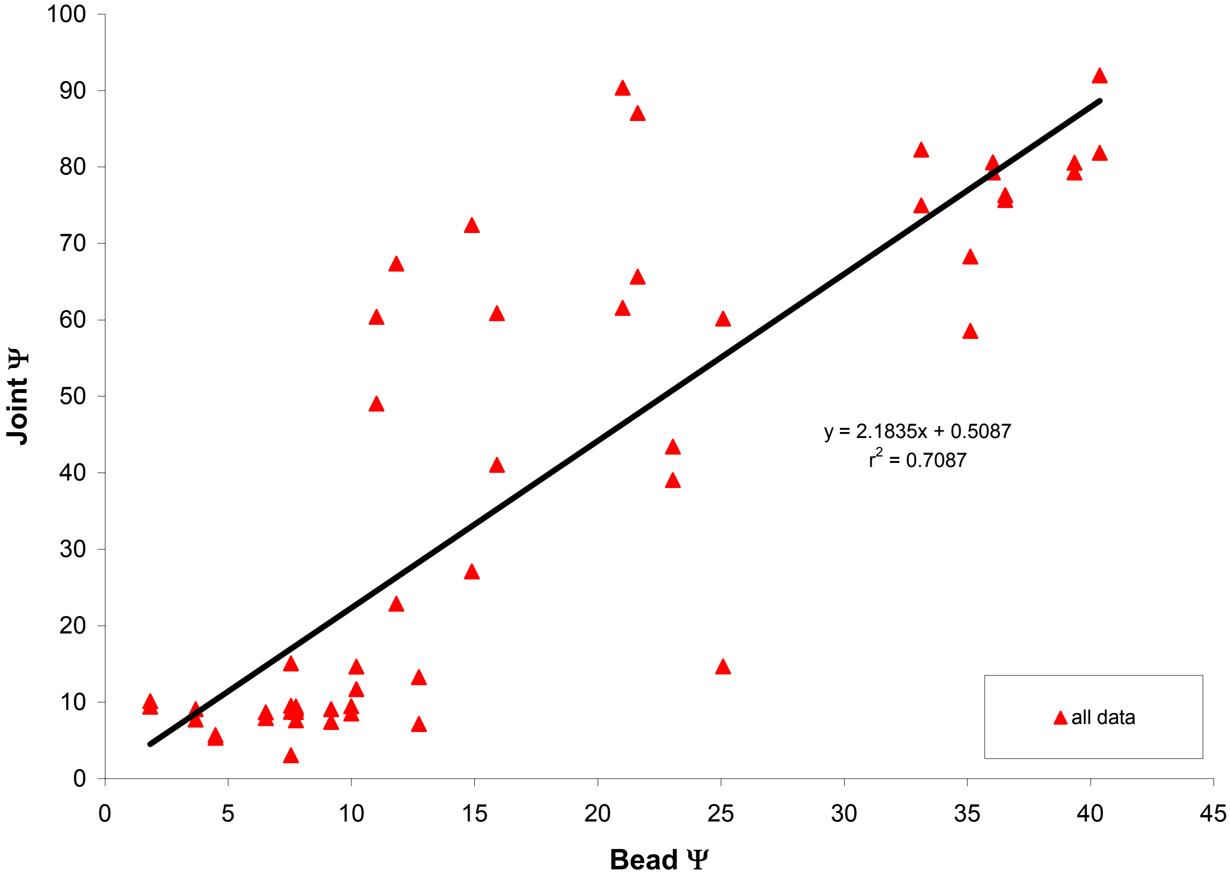


Fig. 8. Correlation between bead and joint quality parameter (Ψ), all data

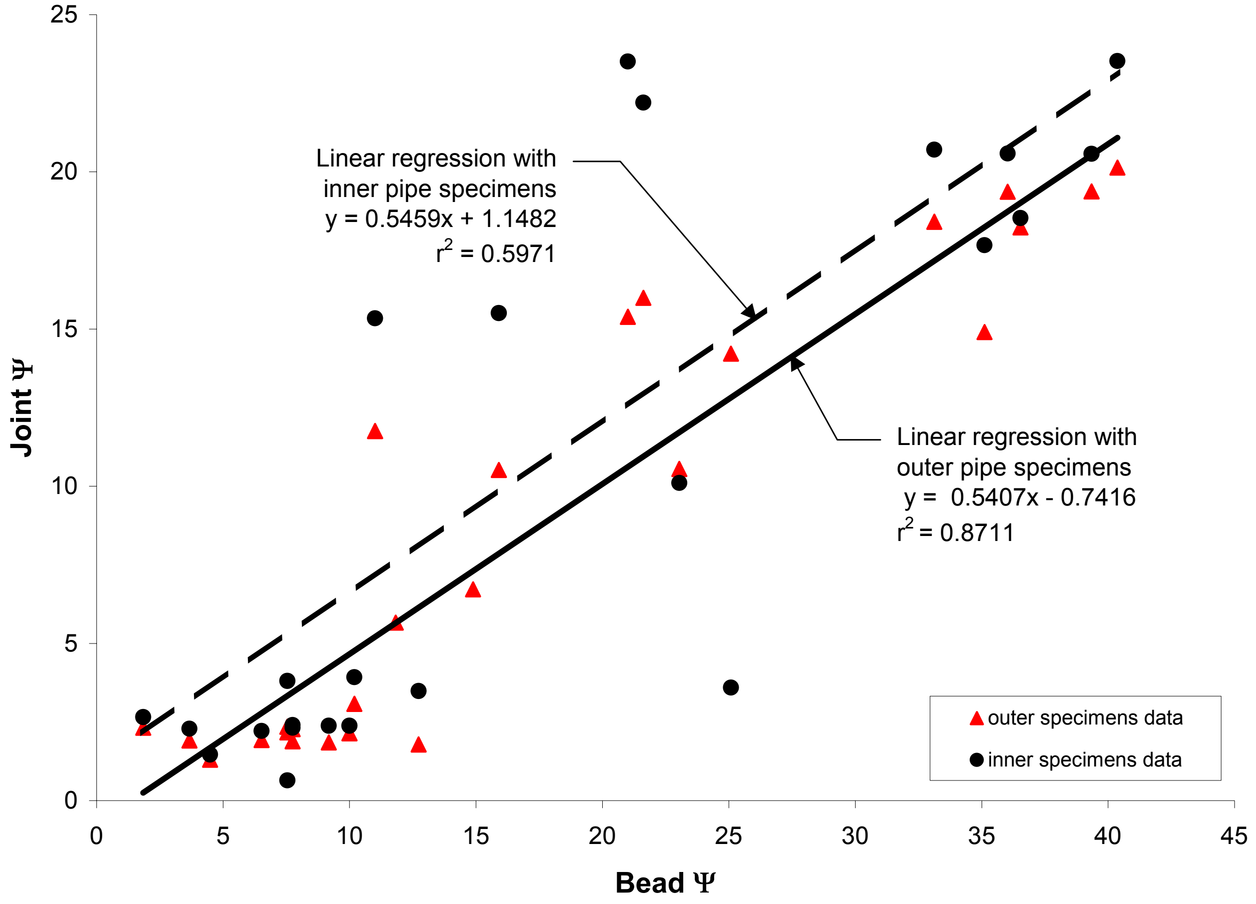


Fig. 9. Correlation between bead and joint quality parameter (Ψ), with inner or outer joint specimens

Figure Captions

Fig. 1. Schematic representation of material flow during fusion joining (not to scale)

Fig. 2. Dimensions of joint (a) and bead (b) dog-bone shaped specimens

Fig. 3. Example of dust accumulation on welding surfaces for 5 seconds of dust exposure

Fig. 4. Fracture surfaces of joint (a) and bead (b) specimen from Joint 4C, showing cement dust and voids

Fig. 5. F Fracture surfaces of joint (a) and bead (b) specimen from Joint 7A, showing clay dust and voids

Fig. 6. Failure modes of bead (a) and joint (b) specimens

Fig. 7. Typical stress-strain curves and failure modes of bead specimens

Fig. 8. Correlation between bead and joint quality parameter (Ψ), all data

Fig. 9. Correlation between bead and joint quality parameter (Ψ), with inner or outer joint specimens