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Integrity of Polyethylene Butt Fusion Joints

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ABSTRACT

Polyethylene pipes play an essential role in today's modern infrastructures as a standard material for drinking water supply, drainage, and sewage pipelines, natural gas distribution lines, intake and outfall pipelines of desalination plants, district cooling and heating systems, oil & gas industries, nuclear power plants, even as a confinement material for concrete bridges. Polyethylene has a successful track record in these diverse fields due to its excellent chemical and corrosion resistance, easy installation and almost maintenance-free operation, and leak-free fusion welding capabilities compared to ductile iron and concrete pipes.

Polyethylene pipes are joint together to form a pipeline via butt fusion welding, electrofusion welding, or mechanical joints, depending on the size of the pipe and installation conditions. Once employed properly by good quality pipes and fittings, and certified welders following standard procedures, these joints present mechanical strength equal to or better than the pipe itself. However, when deviation from standard welding procedures (temperature, time, and pressure), inadequate welding workmanship (planar flaws due to grease and/or oil residuals, presence of fine/coarse particulate contaminations, foreign particle inclusions), and low-quality pipes with poor distribution of carbon black (CB) come together, the integrity of these welds are compromised.

In this study, different butt-fusion joints were produced using pipes with different degrees of CB distribution, to determine the effect of CB inhomogeneity on the integrity of butt-fusion welds of polyethylene pipes. Uniaxial tensile tests on waisted tensile specimens were used to assess short term mechanical integrity, supported with optical microscopy and scanning electron microscopy (SEM) on fracture surfaces of the butt-fusion joints. Experimental results were discussed with a critical defect size approach, and a minimum level of CB distribution is identified to ensure integrity of butt fusion joints.

INTRDUCTION

Polyethylene pipes have emerged as the preferred option for transporting pressurized water and gas, owing to their resistance to corrosion, earthquakes, and ultraviolet (UV) light. The addition of carbon black (CB) is standard practice to enhance the UV stability of polyethylene pipes exposed to direct sunlight, as it offers protection against photochemical degradation. However, the effectiveness of CB as a UV protector hinges on its concentration and dispersion [1]. Inadequate mixing of CB and natural polyethylene can lead to insufficient dispersion, manifesting as light and dark swirls in microscopic images known as 'windows.' These windows, typically resulting from poor mixing in a single screw pipe extrusion line lacking proper design and mixing elements, indicate lower CB content areas. To mitigate this issue, ISO 4427-1 [2] mandates the use of black pre-compounded polyethylene material in plastic pipe production.

Our previous research [3] highlighted the impact of CB particle distribution on the mechanical properties of polyethylene pipes, revealing that 'windows'—areas devoid of CB—significantly weaken the post-yield strength of these pipes. Since polyethylene pipes are often connected through fusion welding processes, ensuring the mechanical integrity of joints is crucial for their long-term functionality.

In this investigation, various butt-fusion joints were produced using pipes with differing degrees of windows, alongside a reference pipe without windows, to assess the influence of CB inhomogeneity on the integrity of butt-fusion welds. Tensile tests on waisted tensile specimens, which provide the most distinct differentiation between welding conditions, were employed to evaluate mechanical integrity. Optical microscopy and scanning electron microscopy (SEM) performed on the tensile fracture surfaces of the butt-fusion joints confirmed that windows significantly degrade both mechanical performance and joint integrity. Therefore, these CB inhomogeneity windows should be considered a critical defect category in butt-fusion welding procedures for polyethylene pipeline systems.

MATERIAL AND METHODS

High-density polyethylene powder was collected from a polymerisation reactor. This was compounded with antioxidants and CB masterbatch (CBMB) containing 40% CB and 60% carrier resin (made of HDPE) to produce a black pre-compounded (ready-made) material using a counter-rotating continuous mixer (Kobe Steel, Japan). The same powder was also compounded with antioxidants but without CBMB to produce a stabilised, non-pigmented polyethylene compound (NPC).

Pipes with an outer diameter of 110 mm and a wall thickness of 22 mm were produced with a single screw extruder with a screw diameter of 60 mm and a length-to-diameter ratio (L/D) of 33 (Reifenhäuser, Germany). A four-channel spiral die with precise heating control via seven different heating zones was used to shape the pipe. The black pre-compound (or ready-made compound) was used to produce reference pipes with no windows (Sample 1). A dry mixture of

NPC and CBMB was prepared with a tumbler mixer. The mixture was then used to produce pipes with different CB distributions (Samples 2, 3 and 4) by changing the extruder output and keeping all other parameters constant. Descriptions of the pipe samples are given in Tables 1. Further details if pipe production and pipe properties can be found in our previous work [3].

Pipes were butt-fused according to DVS 2207 [4] with welding temperature of 210 °C and welding pressure of 0.15 MPa, by using manual butt-fusion equipment (Widos, Germany). Further details of butt fusion welding parameters can be found at our previous work [5].

Waisted tensile specimens were CNC milled from welded pipe samples according to ISO 13953 [6], and elongated to fracture at a constant displacement speed of 5 mm/min using a universal tensile testing machine (Zwick, Germany) equipped with a 50 kN load cell and a set of fork type grips specially designed for such specimens. All tensile tests were repeated four times for each sample. All specimens were conditioned at 23°C and 50% relative humidity for at least 24 hours after specimen preparation.

CB dispersion and distribution in the weld zone of pipe samples were studied by light microscopy analysis of 15-µm-thick microtomed sections, prepared perpendicularly to the pipe axis (cross-flow) at the weld interphase, as well as parallel to the pipe axis (in-flow), covering the melt affected zone. A Carl Zeiss SteREO Discovery.v12 stereo microscope was used. Percentage of windows (white area fraction, WAF) in each figure are calculated according to the method described in our previous work. Appearance rating of each figure is calculated as per ISO 18533 [7] and tabulated in Table 2. Fracture surface analysis was carried out via digital macro photography (Fujifilm S9500) and a large field of view Leica DM100 stereo microscope. In order to understand the fracture modes, SEM analysis of the fractured samples was carried out with an FEI Quanta 250 FEG SEM instrument.

RESULTS

Figures 1 shows the effect of butt-fusion welding on CB distribution in the in-flow (extrusion) direction. The CB distribution in the weld zone is seen to be strongly dependent on the CB distribution or amount of windows present in the parent pipes. A clear interface cannot be differentiated in the weld zone for Sample 1, indicating homogeneity of material from both pipes, resulting in a continuous weld morphology. On the other hand, for Samples 2, 3, and 4, a drastic change in morphology is seen at the weld zone, wherein the windows are seen to be flattened out in a region of about 1 mm thickness. As a result, the alignment of the flow-fronts changes by 90°, and an interface region with smears perpendicular to that in the pipe can be seen.

Figures 2 shows the effect of butt-fusion welding on CB distribution in the cross-flow direction from 15 µm-thick sections at the weld interphase. It was found that there was a significant difference in the homogeneity of the CB distribution for these samples between the in-flow and cross-flow directions. As expected, the white area fraction at the weld zone of Sample 1 was similar to that obtained for the pipe (close to 0%), for both the in-flow and cross-flow directions, given in Table 2. For Sample 2, although the white area fraction at the pipe and weld zone were similar in the in-flow direction, a significant difference was observed between the in-flow and cross-flow directions. This is attributed to flattening of windows at the weld interphase during welding. The difference in white area fraction of Sample 3 in the in-flow and cross-flow directions was not significant, but the windows appeared to be more blurred at the interphase, indicating a certain level of shear mixing perpendicular to the pipe axis during welding. This phenomenon become clearer for Sample 4, where the distinct borders between the windows and matrix become more interfused and co-continuous. The width of the most prominent window increased dramatically for Sample 2, whereas that of Samples 3 and 4 remained the same as their respective parent pipe samples.

The tensile test results of waisted specimens from welded pipe samples are summarized in Table 3. Figure 3 shows tensile curves of each specimen for each sample. All specimens of Sample 1 showed ductile failure (Figure 4a) away from the fusion interphase after reaching a maximum at the yield point, following the typical stress–strain curve of butt-fusion joint tensile specimens. In contrast, all specimens of Sample 2 showed brittle-like failure (Figure 4b) at the fusion interphase before yielding. Two out of four specimens from Sample 3 (Figure 4c) and one out of four specimens from Sample 4 (Figure 4d) also showed brittle failure at the fusion interphase. Accordingly, the average energy required to break the specimens was found to be significantly different for the tested samples.

Table 1 Description of pipe samples.

Sample No	Sample Description	Material	Note
Sample 1	Reference Sample HE3490LS	Pre-compounded	Extrusion speed: 115 kg/h
Sample 2	High level of Windows	NPC + CBMB mixture	Extrusion speed: 115 kg/h
Sample 3	Medium level of Windows	NPC + CBMB mixture	Extrusion speed: 95 kg/h
Sample 4	Low level of Windows	NPC + CBMB mixture	Extrusion speed: 70 kg/h

Table 2 Quantification of white areas in CB distribution images obtained from pipes [3] and weld

Parameter	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
% White area - In-flow direction – pipe	0.04	8.75	5.86	4.80
% White area - Cross-flow direction – pipe	0.04	9.86	5.78	4.29
% White area - In-flow – weld zone	0.04	9.03	5.26	3.31
% White area- Cross-flow – weld zone	0.04	21.90	4.39	0.96
Width of most prominent window – pipe (µm)	~0	200–300	80–140	50–100
Width of most prominent window – cross flow weld zone (µm)	~0	400-500	80-160	50–100
Visual rating according to ISO 18553 (from pipe) (µm)	A1-A2	C1-C2	C1	B-C1
Visual rating according to ISO 18553 [18] – cross flow weld zone (µm)	A1-A2	E	C2	B-C1

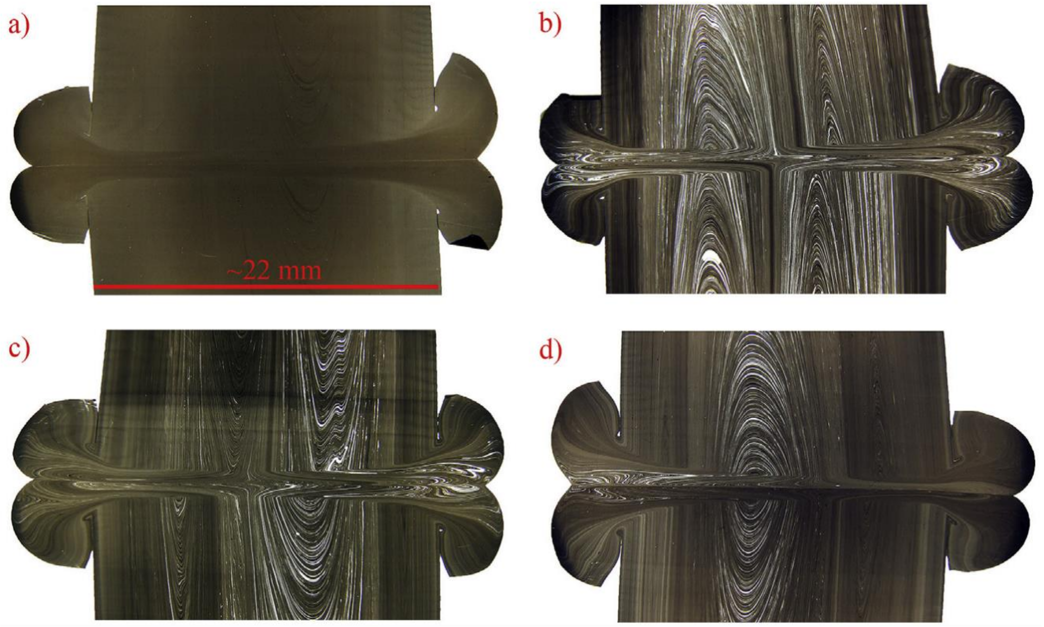

Figure 1 Microscopy images of 15 µm sections (in-flow direction) taken from the weld zone: (a) Sample, (b) Sample 2, (c) Sample 3 and (d) Sample 4.

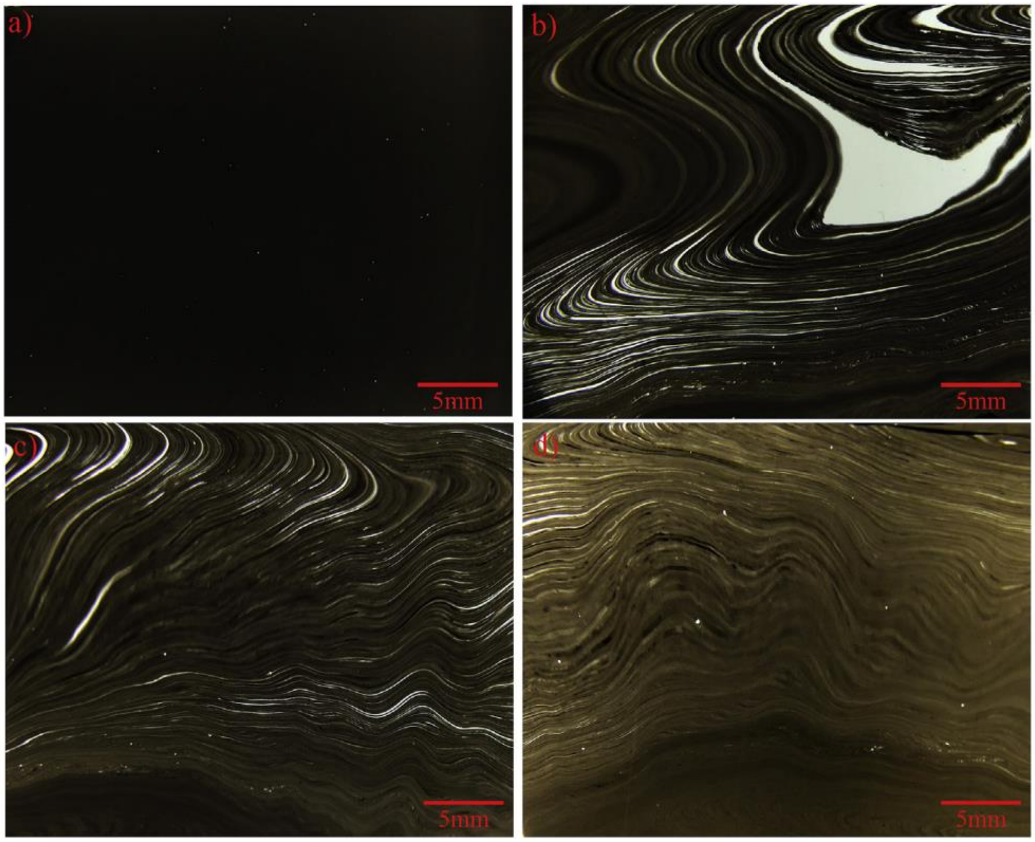

Figure 2 Microscopy images of 15 μm sections (cross-flow direction) taken from the weld zone: (a) Sample 1, (b) Sample 2, (c) Sample 3 and (d) Sample 4.

Table 3 Tensile test results on butt fused pipes

Samples		**Maximum Stress**	**Maximum displacement**	**Work to Break**	**% Brittle Failure**
		MPa	%	Nm	
Sample 1	Average	27.3	35.7	294.3	0%
	Std. Dev	0	4.1	35	
Sample 2	Average	24.7	13.0	93.9	100%
	Std. Dev	1.1	2.6	26.8	
Sample 3	Average	26.7	20.7	156	50%
	Std. Dev	0.9	8.8	70.4	
Sample 4	Average	26.7	31.5	255.4	25%
	Std. Dev	0.3	6.9	48.5	

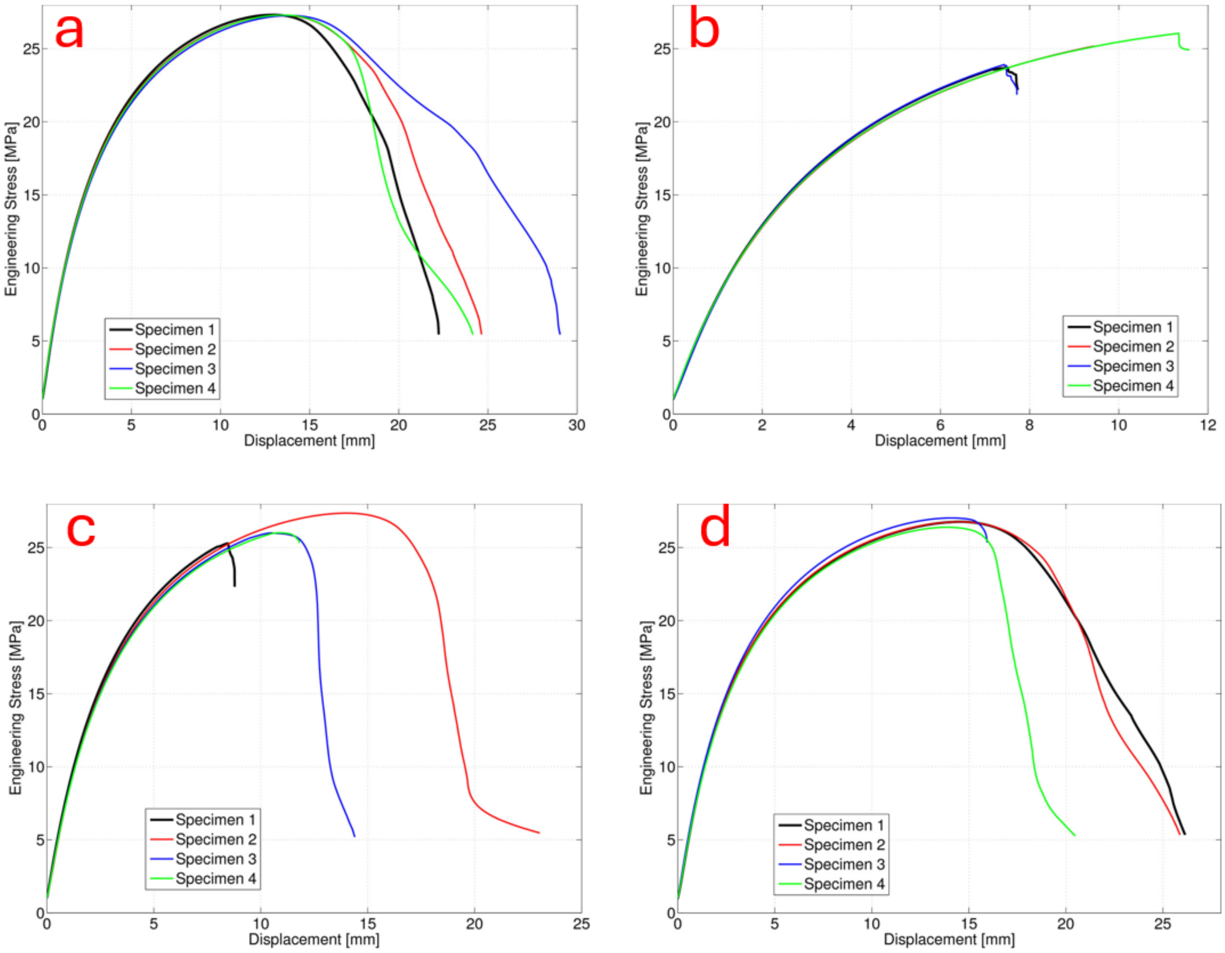

Figure 3 Engineering stress–displacement curves of welded pipe specimens elongated to fracture at a test speed of 5 mm/min, Sample 1 (a), Sample 2 (b), Sample 3 (c), Sample 4 (d)

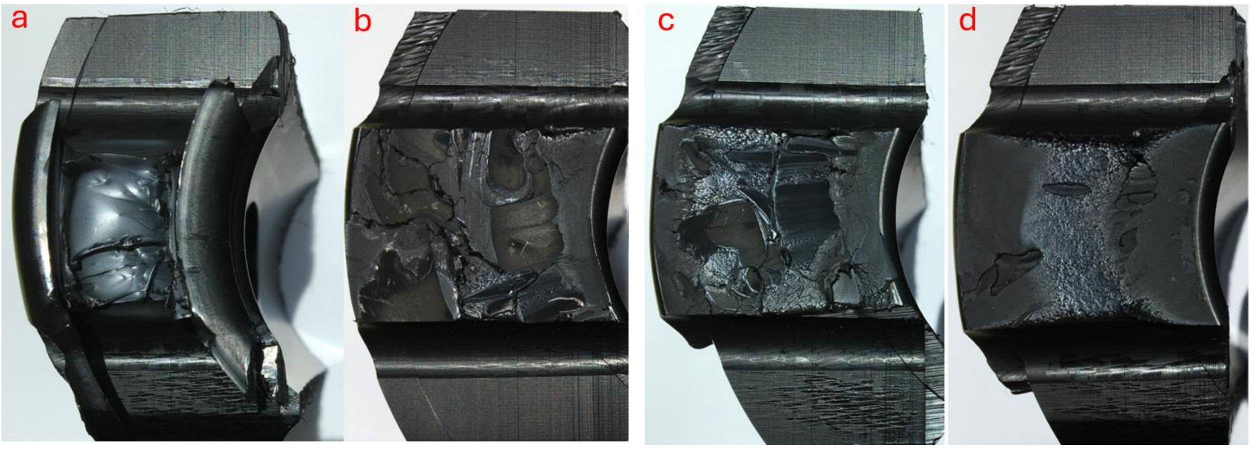

Figure 4 Tensile fracture surfaces of butt fusion welds after tests; (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4

Fracture surface of one of the specimens of Sample 2 with high windows is given in Figure 5a. Widely varying fracture morphologies can be readily seen on the fracture surface, which occurred exactly at the butt-fusion interphase. The presence of a large number of windows is clear, and the bigger windows are observable to the unaided eye. While ductile deformation crazes are not seen in the region marked with 1 in Figure 5a at SEM images (Figure 5b), fibrillation of the material (corresponding to characteristic brittle failure in slow crack growth conditions) is not seen either, as the fracture was rapid and at a strain range below the yield point. To a small extent, flake-like rough pull-outs are observed. SEM analysis of region 2 (Figure 5c), does not evidence any appreciable deformation, yielding, or failure propagation in these regions. This is comparable to catastrophic bulk failure in the brittle mode, which is seen where fine dust or contamination are introduced into the butt-fusion weld, or improper welding conditions, such as lower temperature or shorter times, were used. Unlike the flat–rough regions, no flake-like pull-outs were observed, which means that the crack velocity was higher than in the flat–rough zones. It was also demonstrated by slow crack growth studies that that crack speed increases at windows [8]. A lower magnification SEM image of a region containing a window (marked 3 in Figure 5a), a neighbouring black region, and the interface between the two regions is given in Figure 5d to show the transition of morphology between the two regions. Crazing can be observed at the interface here. In some other regions of the sample, delamination of the windows was seen at these interfaces.

It appears that distribution of CB on extruded pipes measured as white area fraction (WAF) has a significant influence on weld integrity measured as energy required to break per weld test cross-section area (kJ/m^2). This is demonstrated in Figure 6 below. Sample 1, which has no windows shows around 515 kJ/m^2 energy to break value with a standard deviation 60 kJ/m^2. Considering the measured standard deviation, one may claim that energy to break value above 455 kJ/m^2 is acceptable for ductile failures, which means maximum WAF of 2.2 %. Confirming previous works [9, 10]. For safety critical applications such as nuclear power plants etc., where thicker pipes are used, the effect of “windows defects” is expected to be more significant. Therefore, a lower level of WAF, that is less than 1% when measured on 15-micron slices, is suggested by the authors. Furthermore, pipes with windows that has less than Grade A1, A2 or A3 appearance rating according to ISO 18553 has a potential to get worse at the weld interphase by smearing and shearing effect of the welding process and negatively affect the weld integrity.

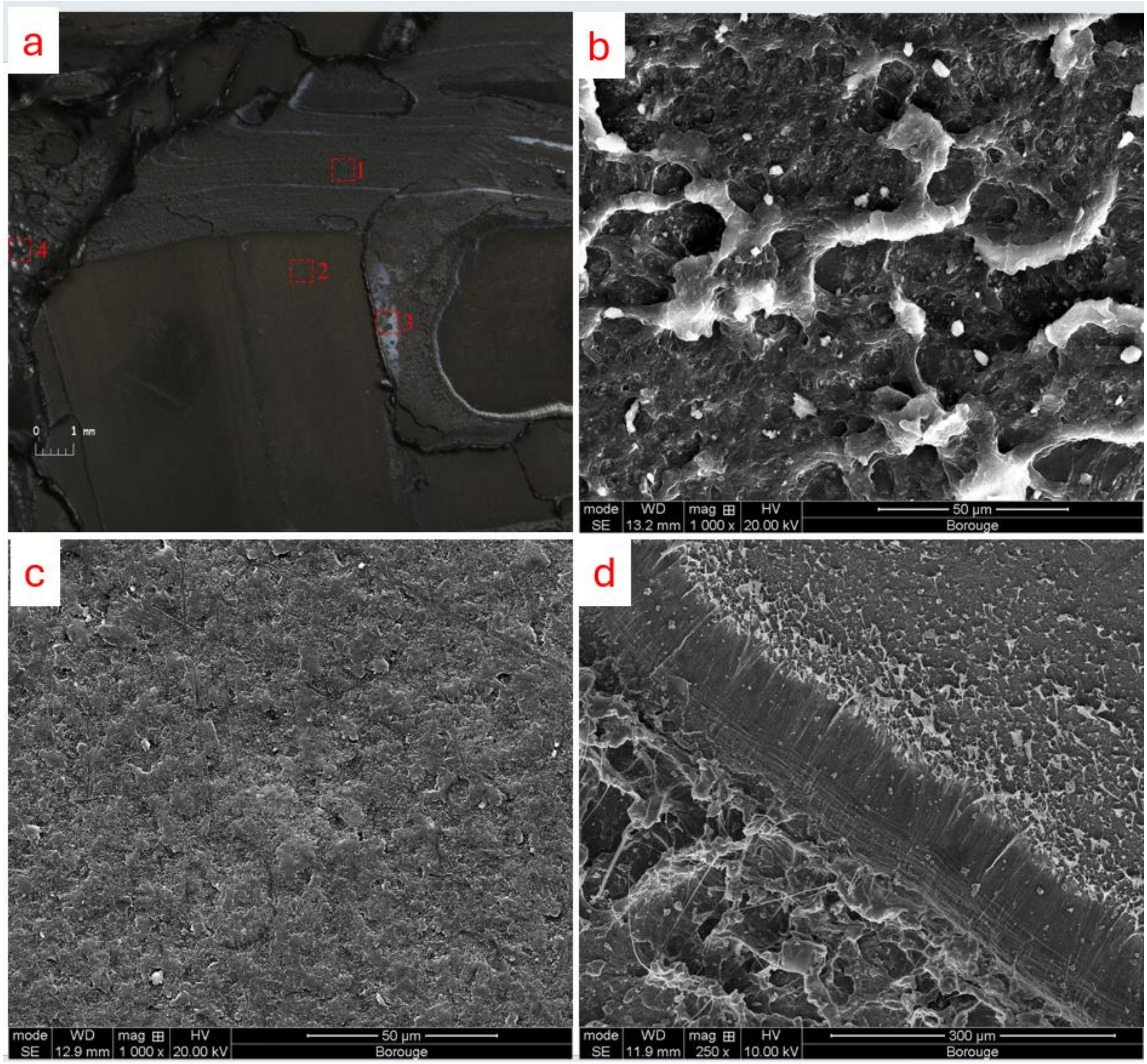

Figure 5 (a) Low magnification microscopy image of fracture surface of butt fused Sample 2 given in Figure 4b, (b) SEM images from region 1 in Fig. 5(a); (c) region 2 in Fig. 5(a); (e) lower magnification of region 3 in Fig. 5(a) showing interface near a window.

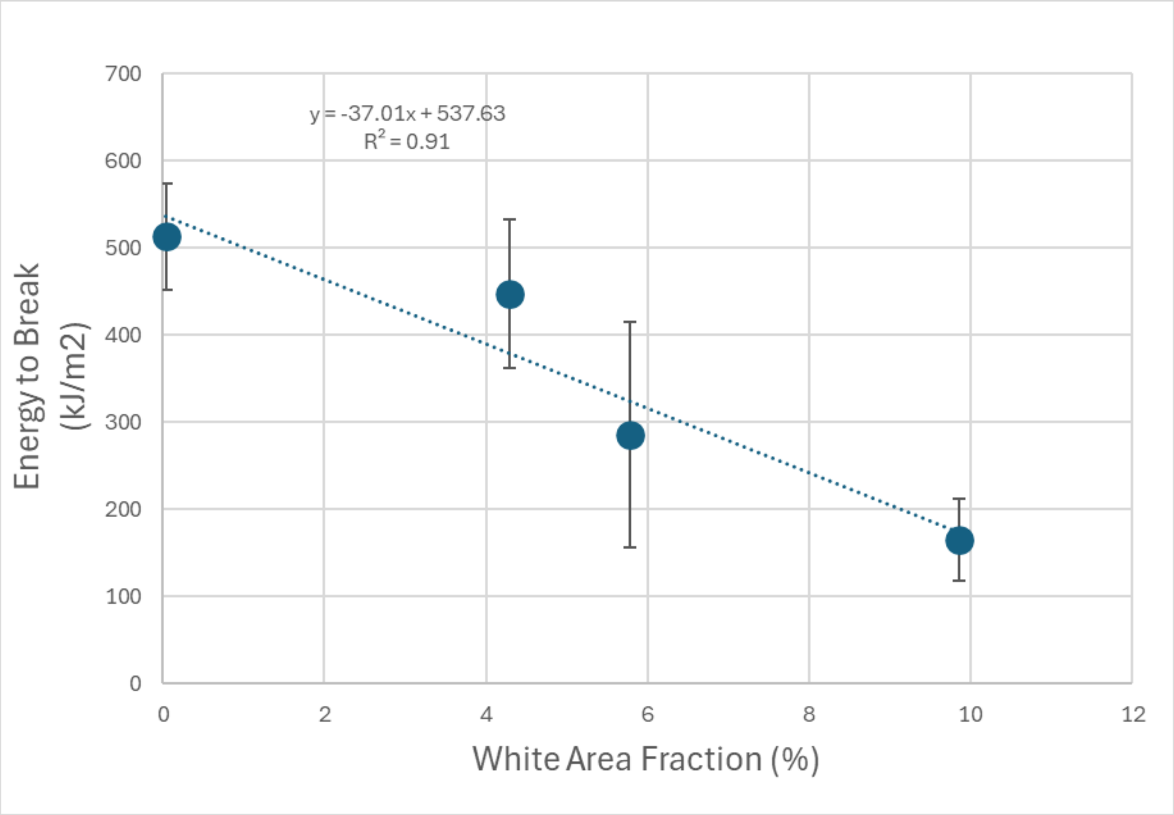

Figure 6 Energy to break value of tensile testing of welded samples as a function of white area fraction

CONCLUSIONS

In this research, four plastic pipes composed of identical polyethylene material but with varying carbon black (CB) distributions were manufactured via single screw extrusion. These pipes were butt-fused utilizing consistent welding parameters. Tensile specimens derived from the joints were extended to fracture, and their fracture surfaces were examined using microscopy techniques.

For samples exhibiting inhomogeneous CB distribution (windows), the welding process tends to generate a morphologically discontinuous interface, with flow-fronts re-aligned perpendicularly to the original flow direction. This re-alignment, coupled with material flattening during joining, significantly enlarges both the size and number of windows. The impact of these morphological transformations, relative to CB distribution, aligns well with the observed brittle failure modes in tensile tested samples post butt-fusion welding. Conversely, the weld zone of pre-compounded material displayed continuous morphology, without any notable signs of interface formation at the weld zone. This consistency is mirrored in the tensile test results, which showed exclusively ductile type failures.

Experimental observations revealed that windows smaller than 100 µm, which do not notably impair the mechanical properties of the original pipes, can expand significantly at the butt-fusion interface due to melt shearing perpendicular to the pipe axis. This expansion can severely degrade mechanical properties and compromise pipeline integrity. Pipes with windows exceeding a white area fraction of 2.2% pose substantial risks to butt fusion integrity. Achieving 100% safe welds necessitates a white area fraction under 1% (measured on 15-micron slices), particularly for thick-walled pipes used in safety-critical applications. Therefore, it is crucial to ensure a highly homogeneous dispersion and distribution of CB in polyethylene pipes with Grade A1, A2 or A3 appearance rating as per ISO 18553, thus eliminating windows to enhance resistance to photochemical degradation and improve the overall mechanical integrity of polyethylene pipelines.

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