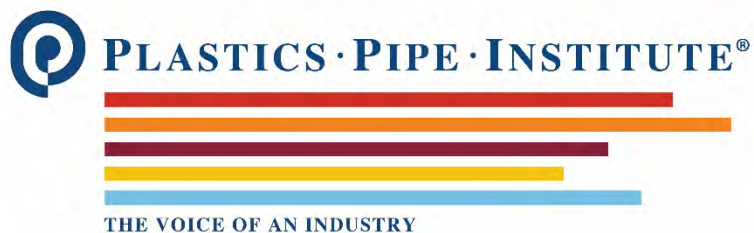


Polyethylene Pipe Butt Fusion
Structure, Process, and
Terminology
TN-51
2018



POLYETHYLENE PIPE BUTT FUSION STRUCTURE, PROCESS, AND TERMINOLOGY

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Polyethylene Pipe Butt Fusion Structure, Process, and Terminology

The purpose of this Technical Note is to impart a basic understanding of the fusion joint and its sub-structure, with the plane of co-crystallization across which the long polyethylene molecules inter-diffuse (knit together) to form the full strength joint. The roll back beads are an indication of a correctly made butt-fusion, however the actual joint is the plane of co-crystallization, which is centered between the dual beads.

Butt-Fusion of polyethylene plastic pipe was pioneered in the USA by industry 'founding fathers' among whom are Ole Larsen, Bob Weaverling, Bud Bridenstine, John Merideth, Jean Louthan, Paul Petro, and others, most of whom began extruding and fusing polyethylene pipe in 1958, as employees of Phillips Petroleum's oilfield **Drilling Specialties Co.** (abbreviated initials: DRISCO), which evolved into Driscopipe® in the late 1970's. Drilling Specialties Co. made the first hand operated flat-heater plate fusion machines heated by an acetylene torch with an embedded oven thermometer. Later an associate company was invited to assume the manufacture of fusion equipment so DRISCO could focus on extrusion of high density polyethylene pipe. As a result, today we all enjoy the benefit of quality fusion machines across the world.



Figure 1: Natural Color Polyethylene Pipe being Fused, 1959, in Caney, Kansas

The solid semi-crystalline polyethylene material melts, technically, at about 257°F, and turns into an amorphous mass of variable length molecules, thermally mobilized by the applied heat energy. As the temperature is further raised to 425°F, the polymer macro melt viscosity reduces, reflecting the increased molecular motion.

As the constant temperature heater plate is left in contact with the face of the melting pipe, the crystalline portion of the HDPE chains 'un-fold', and the melt increases in volume by 28%. This explains the reason that a circular melt-bead forms around the perimeter of the pipe end on the flat heater plate, even though the fusion machine pipe clamps are locked into position. The increase in volume has to go somewhere, so it is pushed out radially around the perimeter of the melt face. Obviously, with increasing pipe diameter and wall thickness, the melt-bead size increases. With increasing contact time, the depth of melt increases, up to a certain axial limit. In the axial direction of the pipe, there exists a distance of thermal gradient from 425°F down to 73°F, which might be a total distance or axial 'depth' of about ¼ inch to ½ inch, depending upon the pipe diameter and wall thickness. From the melt face at 425°F along a short distance, the temperature drops to its crystallization / solidification temperature, at which point the polyethylene is molten on one side and hot, but solid, on the other side; from there further along the axis of the pipe away from the heated end, the temperature drops to ambient temperature.

The flow viscosity of the polyethylene 'melt' is a function of its temperature. The 425°F polyethylene melt flows more easily than at 350°F, than at 280°F. At 240°F, the polyethylene is malleable, but solid, and does not 'flow'. So, when the two melt faces are co-joined with axial force, the HDPE pipe face melt volume flows radially until the axial force, from the increasingly viscous flow resistance of the variable temperature melt depth, equals the applied hydraulic force. From there, the hydraulic pressure remains applied and the clamps moveable, to compensate for additional axial thermal contraction as the hot melt mass thermally contracts during cooling. If the clamps became 'locked' after initial bead formation, the thermal contraction of the melt volume could pull the interface apart, partially or totally; so the clamps have to move with the axial melt shrinkage.

Figure 2 illustrates the cross-section of a 12-inch IPS DR 11 fully formed flat heater plate butt-fusion's outer (top) and inner (bottom) beads. The OD bead is typically 'tight' to the OD of the pipe, because the outward radial melt flow is formed in tension, which tends to pull the melt bead 'backwards' to the pipe OD. The ID bead melt flow is formed in circumferential compression as its formation decreases the ID, which tends to push the bead 'off' the ID pipe wall. In larger pipe diameters and thick pipe walls, for example, the ID melt bead formation will flow radially to the ID and may not lie completely back against the ID pipe surface.

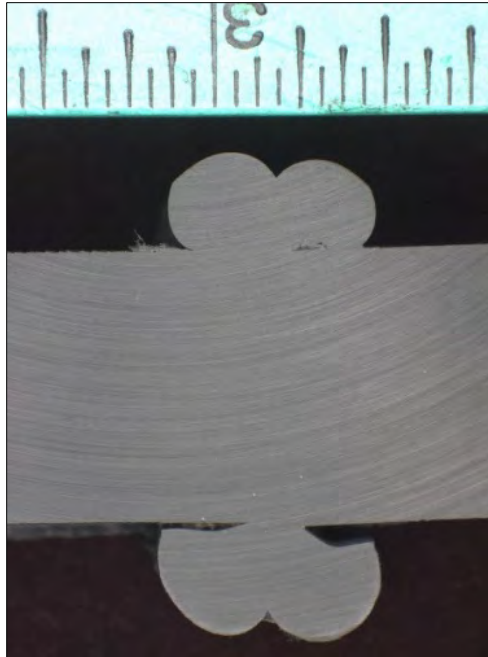


Figure 2: 12-inch IPS Pipe, DR 11, Fusion Joint Cross-section (ground flat)

Figure 3 illustrates the same 12-inch IPS DR 11 butt-fusion joint cross-section, which has been subjected to mild **'heat-reversion'**. Heat reversion is a process of slowly applying hot gas, in a specific temperature range, to the fusion joint cross-section surface to relax the molecular flows, enabling them to reveal their flow pattern. Figure 3 shows clearly the center plane of co-crystallization across which the faces of the two pipe ends molecularly entangle into each other by contact diffusion and thermal mobility.

The thickness of the plane of co-crystallization is in the range of 25 to 50 microns thick (0.001 to 0.002 inches), which is approximately the limit of the inter-molecular diffusion depth at melt temperature.

In Figure 3, the plane of co-crystallization is **"THE JOINT"**, the co-joining of the two ends. The melt flow and melt beads are an artifact of the whole process, but they are not the **"THE JOINT"**.

Figure 3 also clearly reveals the boundary plane separating the melted region from the solid pipe wall. The mass between the plane of un-melted, solid pipe wall and the plane of co-crystallization is the **melt-flow-zone (MFZ)**.

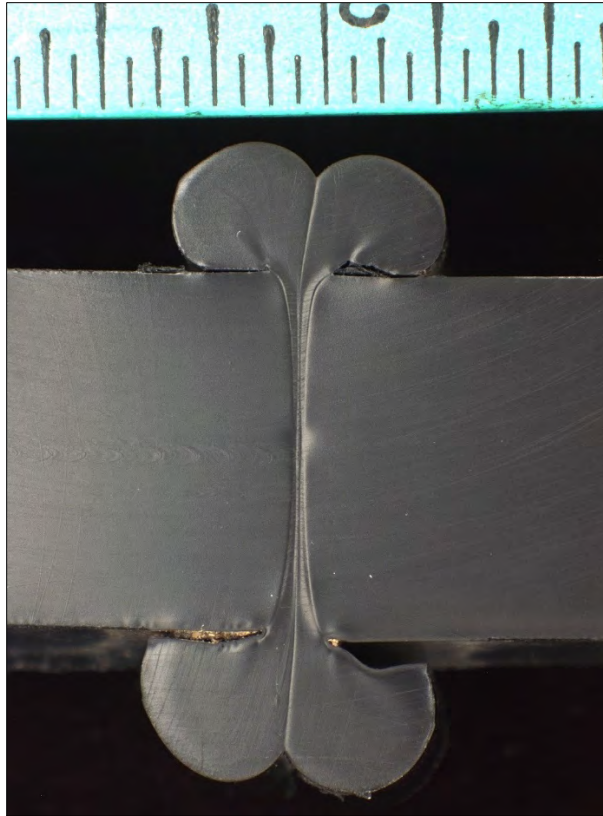


Figure 3: 12-inch IPS Pipe, DR 11, Fusion Joint Cross-section, after Heat-Reversion

Assume for a moment, that the pipe wall thickness can be separable into an outer $1/3^{\text{rd}}$, a middle or center $1/3^{\text{rd}}$, and an inner $1/3^{\text{rd}}$. Figure 4 illustrates that the fusion-joint's plane of co-crystallization is formed from the center third (the middle) of the pipe wall thickness.

By following the colored lines of the layered pipe wall cross-section, one can see that the outer bead is formed from the outer one-third of the pipe wall facial melt volume; the inner bead is formed from the inner one-third of the pipe wall facial melt volume, and the fusion-joint line of co-crystallization is formed from the radial flow of the middle one-third of the pipe wall. The face of the 'central third' is radially stretched in diameter (like pie-dough being rolled out into a larger diameter). Across this hot, radially stretched facial plane, the hot mobile molecules on each pipe end come into intimate contact under axial pressure, such that the molecular van der Waals' force pull the molecules from the two faces together (molecular wetting). Thereafter, the long-chain HDPE polymers wiggle and virtually diffuse into each other (like salt crystals diffuse into water), gradually slowing in mobility and motion as they reach maximum diffusion penetration depth. As the thermal conduction of the near-by cooler, solid-pipe draws heat away from the melt, the solidification process advances forward to the plane of co-crystallization. Within the melt-flow-zone, when the temperature drops below about its crystallization temperature, the solidification process is complete and molecular diffusion entanglement stops.

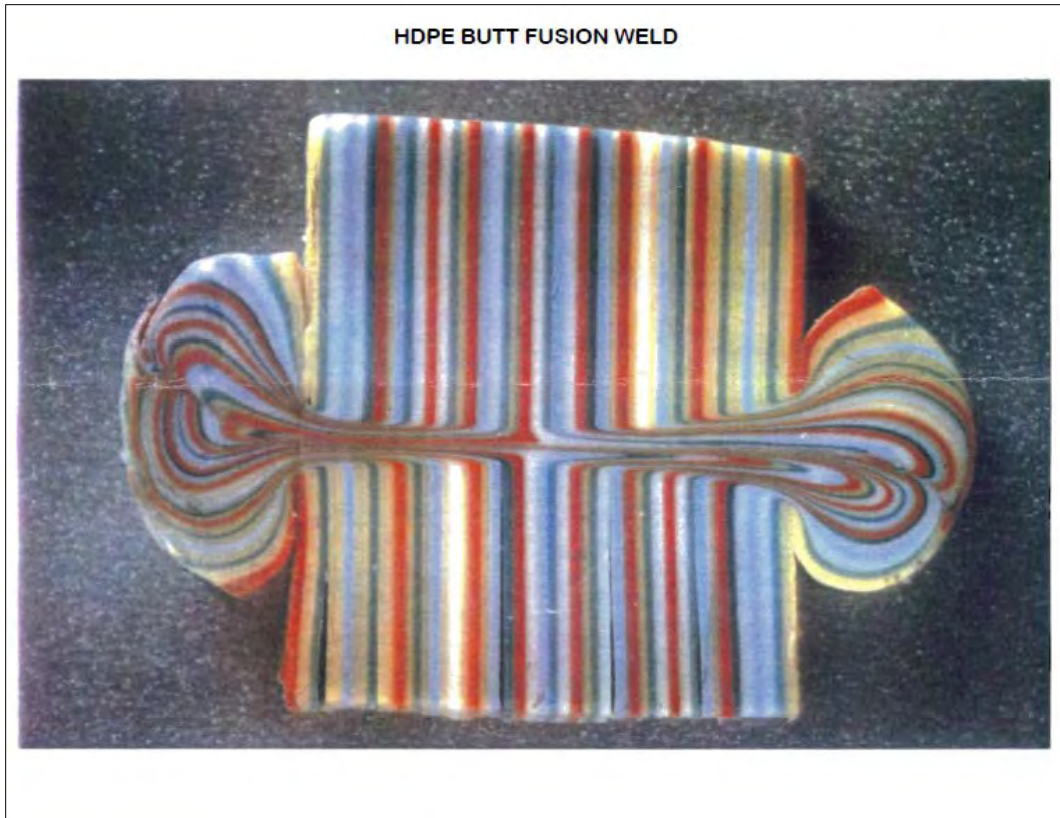


Figure 4: Axial Heating, Axial Conduction, Radial Melt-Flow, Plane of Co-Crystallization, Bead Structure

Intermolecular diffusion and entanglement is a time and temperature driven function. Temperature mobilizes molecular ‘wiggling’ because of the heat energy imparted into the molecule. Heat is a reflection of molecular motion. Time is required for all the molecules to find ‘holes’ into which the molecule can fit and slip, sort of like a bundle of worms moving over each other. It takes time to wiggle between each other to make forward progress. Outside of normal fusion parameters and best practice, when the ‘cool’ zone of the melt-solid pipe-wall boundary is forcibly moved forward with excessive force or pressure against the interfacial plane of co-crystallization, this action radially squeezes out most of the melt volume into the melt bead, leaving little residual heat between the pipe ends, and the cool pipe end zone rapidly sucks the reduced latent heat from the interfacial diffusion layer, quenching the temperature and rapidly solidifying the co-crystallization plane prior to the time required to achieve maximum diffusion entanglement depth, such that a ‘non-fusion’ joint is formed.

NON-FUSION: an un-acceptable, rejectable polyethylene pipe joint formed outside of the standardized fusion specification parameters and procedures, which results in insufficient cohesive entanglement throughout the ‘plane of co-crystallization’ because of insufficient interfacial diffusion (due primarily to abbreviated time to solidification), either of the numbers of molecules or of depth of molecular inter-penetration, or both, of the HDPE molecular chains across the interfacial boundary into the opposing melt face, which results in less than acceptable properties, performance characteristics, or longevity.

The strength or fracture resistance of an HDPE pipe-wall fusion joint is assumed to be dominated by the “n” number of molecules which diffuse across the interface during the fusion process prior to cooling crystallization. The number of effective crossings per unit area of coalesced interface, after equilibrium contact conditions have been reached, is a significant parameter. An effective crossing is defined as a polymer chain which contributes to fracture resistance through either chain scission or viscoelastic dissipation. Specifically, the strength of the joint is equal to the total energy required to either fracture all the molecular chains and/or to pull these molecules out of the “tube” created by their surrounding physical entanglements and back across the interface. The greater the number of effective molecular crossings, the longer the molecule, or the deeper the interpenetration distance, the greater will be the resistance to joint fracture.

Figure 5 diagrams the seven zones in the well-made polyethylene pipe fusion joint. This figure was developed from the fusion joint of 36-inch IPS DR 9 polyethylene pipe (ref: Figure 6 pipe wall), used to convey ‘essential cooling water’ to a nuclear power plant steam turbine’s condenser.

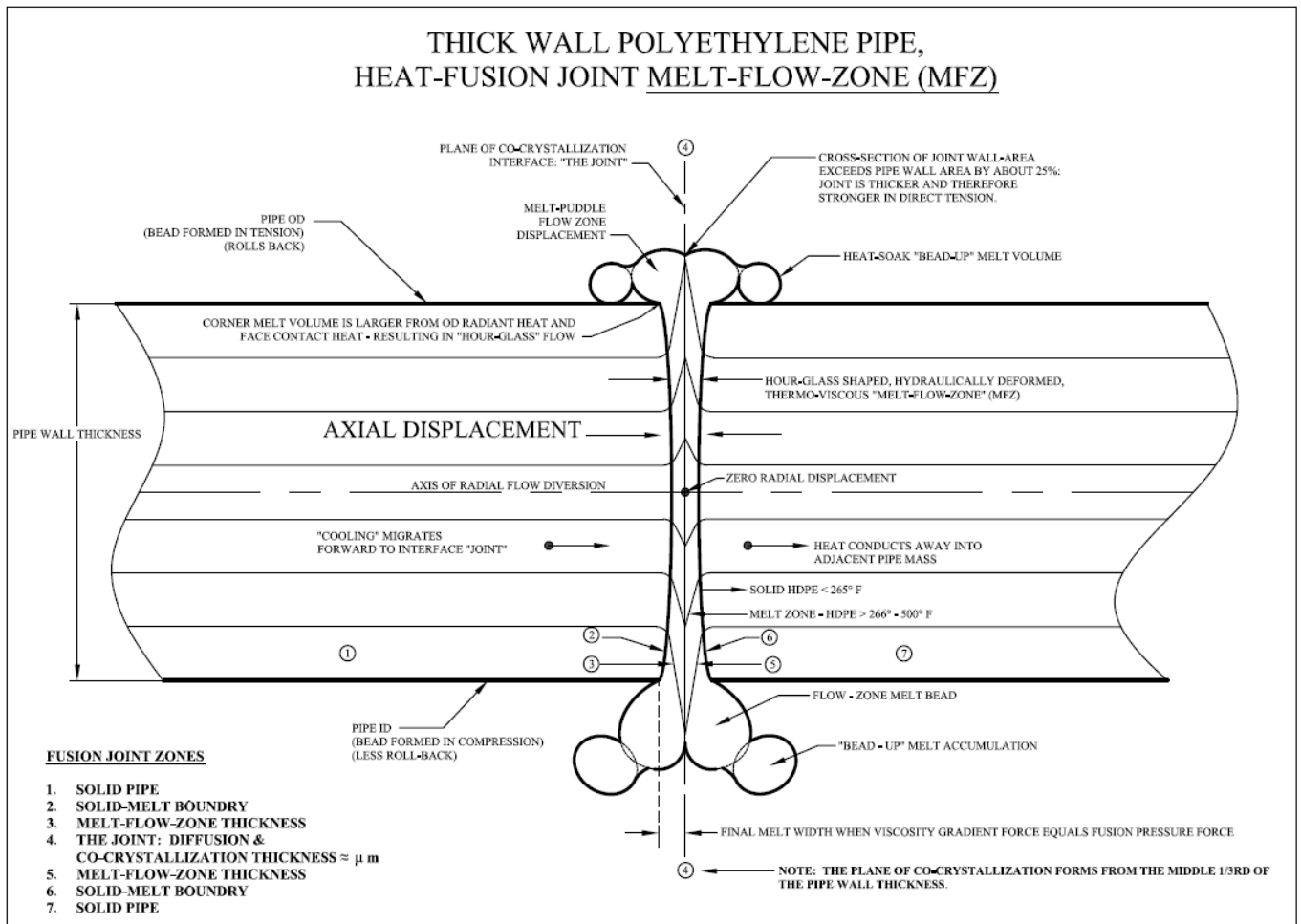


Figure 5: Seven (7) Zones within the Polyethylene Pipe Butt-Fusion

Fusion Bead Removal

As illustrated in Figure 3, the melt-flow zone's external (OD & ID) roll-back beads are artifacts of the fusion joining process. The actual '**JOINT**', is the coalesced zone, scientifically referred to as the circular "plane of co-crystallization" or "line of co-crystallization", made visible as the 'center-line' of a HDPE pipe fusion which has undergone "heat reversion". The roll-back beads are 'excess material' which do not contribute to the fusion joint's tensile strength.

Roll-back OD and ID beads may be smoothly and properly removed, by various mechanical means (router, planning device, skiving knife, bead trim tool, etc.) provided their removal does not trim the root of the co-joined beads below the surfaces of the adjoining pipes (i.e.: does not reduce the interfacial fusion area to less than the adjoining pipes' maximum contact wall area). Commercial bead removal tools are available and are the preferred method of bead removal. If bead removal is to occur, it should not be performed until sufficient cooling has occurred to prevent the resulting root of the co-joined beads shrinking below the surfaces of the adjoining pipes. Removal of the fusion bead with power grinders or sanders is not recommended.

Proper bead removal does not affect the mechanical strength of the fusion joint. Fusion joint beads are seldom removed in North America. Circumstances for bead removal, in North America, are typically associated with compressed HDPE tubular liners within steel pipe, food processing, fish farming, tight sidewall fusion or sidewall electro-fusion saddles, etc. In these scenarios, removal of internal and external beads has been practiced for over 40 years.

Unintentional bead removal: Partial bead removal from pipe and fittings by force encountered during installation, insertion, construction, buried, pipe inserting, HDD, etc., does not affect the joint's integrity and strength, as the roll back beads are excess melt-flow material formed outside of the actual joint between the fused pipes' OD and ID.

Note: In certain cases like stub-ends with bolt-rings, tight fabrication fusion beads must be trimmed where commercial beads removal tools will not work in the confined space. A very sharp hand skiving blade tool with rounded front tool may be used with extreme care, tangent to the pipe OD, so as to minimize possible gouge to the pipe OD, and provided the bead removal does not trim the root of the co-joined beads below the surfaces of the adjoining pipes (i.e. does not reduce the interfacial fusion area to less than the adjoining pipes' maximum contact wall area). Holding the skiving knife or cutting device in a proper manner to mitigate potential damage to the pipe surface is of utmost importance. Successful hand trimming can and has been done in the past with proper tooling modifications, training, and careful use.

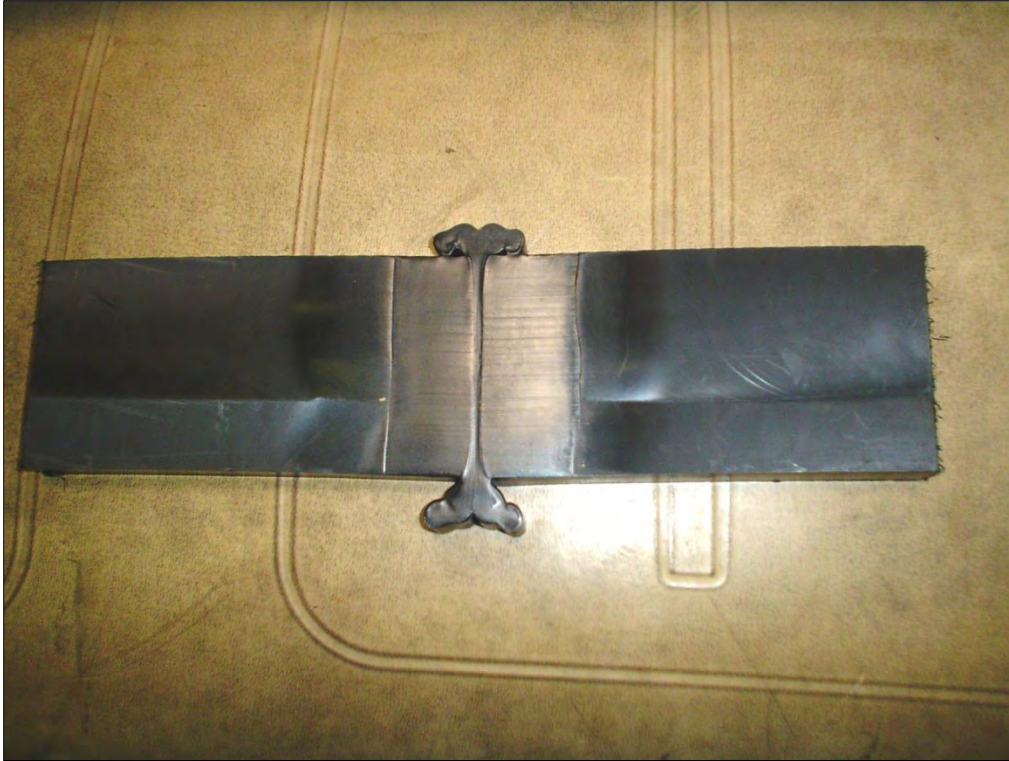


Figure 6: Heat-Reversion Machined Pipe Wall -- 36-in IPS DR 9 PE4710 Pipe Butt-Fusion Cross-Section, with larger melt bead-up lobes

APPENDIX

Autohesion is the spontaneous self-adherence and bonding by molecular diffusion and migration, of two adjacent surfaces of the same material, without the use of an adhesive. Autohesive materials diffusion bond only to themselves. Pipe Grade HDPE polymer is an autohesive material.

To form the autohesion bond during HDPE pipe wall fusion, the polyethylene must be able to flow and coalesce after contact. It is a three-stage process. 1. In the first stage, wetting must be initiated. This is enhanced by surface preparation such that the surface is smooth so the maximum number of molecules can come into intimate contact between the two surfaces. 2. In the second stage, progressive molecular contact is realized as the mating surfaces flow together under the action of attractive molecular forces and applied pressure. 3. In the third stage, coalescence takes place by vanishing of the boundary between the two surfaces due to self-diffusion with molecular chain entanglement, which is the basis for autohesion theory established by Voyutskii and Vasenin. (Ref: 1, 2)

Complete coalescence is time dependent; it occurs primarily in proportion to the rheological viscosity and mobility of macromolecules and/or their segment lengths. Coalescence is accomplished by diffusion movement of macro-molecules (macro-brownian movement) or their segments (micro-brownian movement). Coalescence of two surfaces into one solid involves a limited migration distance for molecular diffusion; there is a limit on the possible distance for diffusion of polyethylene molecules from one surface into another, based on the degree of temperature induced molecular mobility, molecular chain length or chain segment length, inter-and intra-chain free-volume “tubes” or void space, path-way tortuosity, adsorption, van-der-Waals hydrogen-bonding attraction force, flow agitation, contact pressure, etc.... The self-diffusion coefficient of linear molecular chains varies inversely with molecular weight. In broad molecular-weight polyethylene, the shorter chains will tend to inter diffuse more rapidly than long ones. With sufficient time above the melt temperature, the interpenetration distance increases to its limit, and eventually the original contact faces vanish and the zone becomes indistinguishable from the bulk material as the molecules become fully entangled as one solid.

Once the optimum thickness of coalescence of melted HDPE is achieved, the HDPE molecular bonding is solidified by natural cooling crystallization into the semi-crystalline form of HDPE at room temperature.

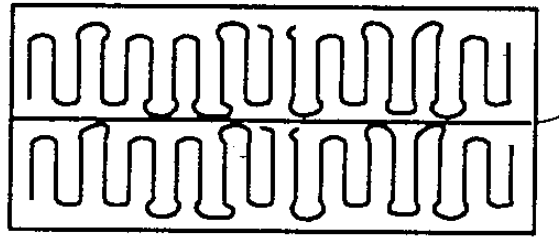


Figure A 1: Interface Upon Wetting Contact (showing polymer molecular chains)

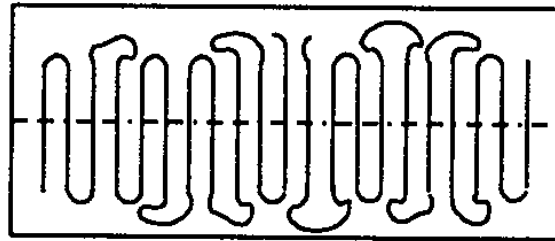


Figure A 2: Autohesion Diffusion and Coalescence vanishes the interface

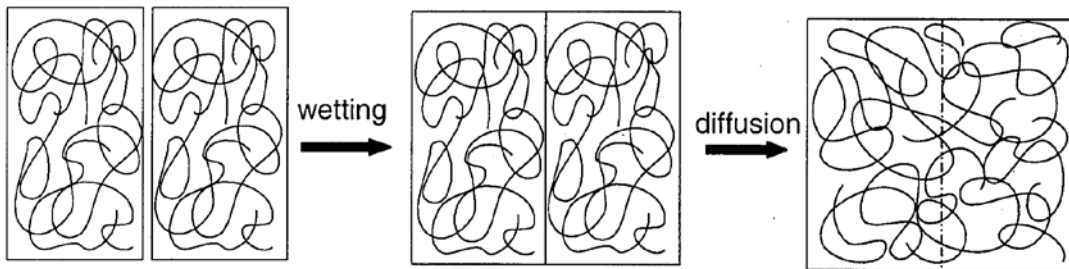


Figure A 3: Diffusion Entanglement and Co-Crystallization into one bulk solid

In a pipe fusion joint, the melt-flow zone and the roll-back beads are artifacts of the fusion joining process. **THE JOINT**, is the coalesced zone, scientifically referred to as the “plane of co-crystallization” or “line of co-crystallization”, visible in the center of a HDPE pipe fusion which has undergone “heat reversion”.

Ref:

1. Voyutskii, S. S. 1960. *Autohesion and Adhesion of High Polymers* (Izdatel'stvo nauchnotekhnicheskoi literatury, RSFSR, M.). See also S. S. Voyutskii, *Autohesion and Adhesion of High Polymers* (Interscience Publishers, N.Y., 1963)
2. Vasenin, R. M. 1963. *Collection, Adhesion of Polymers*, 53, 58 Publishing House of the U.S.S.R. Academy of Science, M..