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PECULIARITIES OF TECHNOLOGY AND MODERN TRENDS IN THE FIELD OF BUTT WELDING OF POLYETHYLENE PIPES (Review)

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Pipelines for the transportation of natural gas, cold water supply and drainage are one of the most significant elements of urban and rural infrastructure. Pipelines from polymer materials, in particular polyethylene, are a modern alternative to steel pipelines, which during 15–20 years of operation are destroyed under the influence of chemical and electrochemical corrosion. In the world and in Ukraine, almost all new distribution pipelines for gas, cold water supply and drainage are constructed from polyethylene pipes. In Ukraine, especially in large cities, a practice of replacing old worn-out steel pipelines by new polyethylene ones and renovation using the method of inserting a polyethylene pipe into steel pipeline has become widespread. One of the most technological methods of joining of polyethylene pipes of almost the whole range of outer diameters is butt welding with a hot tool. The equipment for this welding method is currently not manufactured in Ukraine. The imported installations for butt welding of polyethylene pipes are operating according to the conventional technological scheme developed a long time ago, some elements of which, due to the improvement of the polymer materials themselves, can be revised and simplified preserving a high quality of final welded joints. The aim of the work is to review the state of the art in the field of butt welding of plastic products, first of all, polyethylene pipes with a hot tool and its modifications, which are the most interesting from the technological point of view. 28 Ref., 5 Figures.

Keywords: *butt welding with a hot tool, plastics, polyethylene pipes*

Joining of polyethylene pipes is virtually the final and, on the other hand, the most responsible stage in the whole complex technological chain of construction of a technological pipeline. The world and domestic experience proves that in most cases such joining is performed by welding, in particular using butt welding with a hot tool. Welds play a decisive role in providing the reliability of the entire polyethylene pipeline. Therefore, in the whole world, a great attention is paid to investigations of technological features of such welds [1–3].

According to the standard documentation, valid in Ukraine, the polyethylene pipes for supplying cold water can be joined by butt welding with a hot tool, taper welding, electrofusion welding, and also mechanically with the help of special clamping parts [4]. Polyethylene pipes for gas pipelines can be joined only by two methods: butt welding with a hot tool and electrofusion welding [5]. As far as mechanical joints of pressure polyethylene pipes are used quite rarely in practice, the main method for joining such pipes during construction of technological pipelines is welding. All three of the above-mentioned methods of welding of polyethylene pipes have long been known. The technology and equipment for them are quite well developed [6–8]. However, taper welding and electrofusion welding need the use of special joining parts: couplings, which increase the cost of construction of pipelines, increase the external dimensions of a butt joint. In addition, these welding methods require a fairly accurate compliance with the geometric shape and dimensions of a pipe and a joining part due to a high risk of formation of lack of penetrations or pores during upsetting of the weld material [9].

Butt welding with a hot tool is currently the most versatile method for joining polyethylene pipes and can be used for the most types and sizes of pipes, except of thin-walled with a wall thickness of less than 5 mm. In recent years, this technology is constantly being developed and improved. It is used for welding pipes of large and superlarge diameter and pipes of new grades of polyethylene composition [10]. The equipment for this welding method demonstrates the tendency to differentiating the design depending on the purpose. For welding in the field conditions, the powerful and robust machines with four clamps are used. In the shop conditions, as a rule, short sections of pipes are welded with the help of stationary machines with rotary clamps. For repair and site works the lightweight welding devices are used [11].

Over the past 30 years, the pipe grades of polyethylene were rapidly developed and passed the evolution from PE 32 to PE 100. In practice, a constant need arises to weld pipes, made of «old» and «new» types of polyethylene. Very often, builders mistakenly consider polyethylene of different grades as similar and equivalent, although they differ significantly by their molecular structure and physical properties [12]. It was experimentally proved that a long-term quality of welded joints of polyethylene pipes, operating under loads, depends on the micro- and macromolecular structure of the material, the peculiarities of which formation should be studied separately for each pair of polymers to be welded. The quality of welded joint of polyethylene pipes is determined, mainly, by thermophysical and rheological processes in the zone of a weld. The butt welding with a hot tool is characterized by a strong flow of a molten material, which in the process of upsetting is squeezed out from the middle of a joint outside as a flash. The kinetic regularities of this process depend on basic parameters of the welding process and, on the other hand, essentially depend on the properties of the polyethylene composition.

The simplest way for supplying the heat energy required for welding of thermoplastic polymers is by the direct contact of the surface of a part being welded with a hot tool. Most often, in such a way the uniaxially-directed parts are butt joined, but this method is also used for other types of a joining. Using the method of heat transfer, this type of welding is often called thermal. In the cases, when a direct contact with the surface of the joint is impossible, the external surface of the parts is heated: this is the so-called welding by indirect heating [13].

The method of butt welding with a hot tool (direct heating) is widely used in practice due to the simplicity of technological process of welding, equipment and rigging. Mainly, this method of welding is used in the construction of polymer pipelines (most of all polyethylene ones) for transportation of combustible gas and water. The other fields of application of thermal butt welding is joining of plastic profiles in the manufacture of window frames, welding of rods, plates and other parts of different structures of plastics. In the recent years, this method of welding with the use of special equipment is used for welding of engineering plastic products in automotive and other industries [14]. The butt welding with a hot tool is used also for welding of composite polymer materials [15].

Traditionally, the butt welding process with a hot tool is performed at a preset value of pressure during upsetting. A typical diagram of the change in working pressure during welding is shown in Figure 1, *a*.

During welding of plastics, having a wide temperature range in a molten condition with a low level of toughness, the traditional butt welding technology with a controlled working pressure is justified (Figure 1, *a*), as far as when the preset pressure is achieved

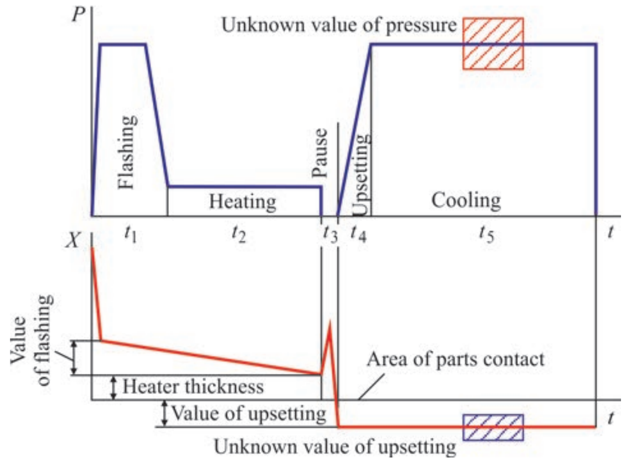

Figure 1. Time diagrams of pressure (*P*) and displacement of the ends of parts (*X*) at different technologies of the butt welding process of plastics (including polyethylene pipes) with a hot tool: *a* — welding with controlled pressure; *b* — welding with controlled upsetting

in the course of upsetting, the molten material can be surely squeezed out into the flash.

During welding of plastics, whose toughness essentially changes depending on the temperature, the technology of welding with a hot tool at a fixed value of upsetting (Figure 1, *b*) is used, as during cooling of surfaces being welded the toughness of the melt can grow to lower than the optimal level as much, that the established level of working pressure will not be able to provide a squeezing out of the melt during upsetting and a normal weld formation. In this case, special devices (usually rests) are applied to control both the value of flashing of the surface of the parts during heating, as well as the value of upsetting, i.e., the zone of flashing during squeezing out of a heated melt into the flash. The same rests determine the final size of the weld after welding. Applying this technology, depending on the specific conditions of welding, the value of working pressure may change, as the melt with a lower toughness will be squeezed out by a lower pressure and vice versa. Similarly, applying the traditional technology, an uncertainty in the value of upsetting exists, which will also depend on the toughness of the polymer melt.

The purity of surfaces of parts to be welded is one of the main factors which provide the quality of joining during butt welding with a hot tool. Contamination deteriorates the integrity of a weld, and the foreign inclusions can act as stress concentrators, which becomes a prerequisite for initiation of cracks under loading. Since most of welded joints of polymer pipes are carried out in the field conditions, the risk of contamination of such welds is particularly significant. The following types of contaminations of the surface of pipes are distinguished: strong contamination with soil, resin and other dirt, negligible contamination with dust, fat and oil traces, moisture on the surface, surface oxidation by atmospheric oxygen, surface erosion under the effect of solar ultraviolet radiation. The automation of welding process with a hot tool should provide the maximum possible cleaning of surfaces of the parts before welding [16].

A direct nature of heating surfaces and their direct contact during upsetting specifies increased requirements to the geometry of pipe ends being welded. Therefore, in accordance with the requirements of the standards, before welding the fixed and aligned ends of pipes and parts are subjected to mechanical treatment: facing in order to align the surfaces to be welded directly in the welding installation. The maximum allowable value of gaps between the ends to be welded is specially determined depending on the thickness of a pipe wall [5]. The device for facing is usually a complex electromechanical device with specially sharpened blades, which align the surfaces of pipe ends. The process of mechanical facing of pipes substantially complicates the preparation for welding, especially with the increase in the outer diameter of the pipes to be welded. The presence of a complex mechanical facing device, which must be constantly maintained and adjusted, greatly increases the cost of butt welding equipment.

After a proper preparation of pipe ends, welding of the joints begins directly. The use of an external tool for heating the surfaces being joined involves the interruptions in the process of butt welding of pipes. Typically, these are the main stages of the process, which are also divided into stages [17] (Figure 1):

● heating of surfaces of the pipe ends, including the stages of flashing t_1 and heating t_2;

● technological pause t_3, which is necessary for the removal of the hot tool;

● upsetting of welded parts t_4 with a gradual increase in working pressure and cooling of the weld under the pressure t_5 until its final formation.

At the stage of flashing, the pipe ends enter into direct contact with the surface of the hot tool. The heater temperature is preliminary set higher than the melting point of the polymer material, from which the products are made, therefore, the process of ends flashing begins immediately. The heating of the pipe ends is carried out exclusively due to the heat transfer from the surface of the hot tool and a gradual thermal conductivity of the polymer material deep inside the product. The process of ends flashing is necessary to provide their effective uniform heating at a tight contact of pipe surfaces and the hot tool. At this stage, due to melting of the polymer material, all the microroughness of the end surfaces disappears, as well as even the minimal gap between their planes, which could remain after mechanical facing. To accelerate the flashing process, the pipe ends are pressed against the hot tool at a maximum working pressure of 0.2 ± 0.02 MPa (Figure 1, *a*), which causes the active squeezing out of the polymer outwards. The criterion for the completion of a uniform flashing is the formation of small uniform beads of a primary flash along the perimeters of both pipe ends welded [7].

It is believed that in the process of flashing the pipe ends, the heating of the polymer mass into depth almost does not occur, since all the heat, transferred by the heater, is spent for melting the roughness of the pipe surfaces. Upon completion of the flashing stage t_1, the working pressure on the pipes decreases to a minimum value of 0.01–0.02 MPa and the heating stage t_2 begins, the duration of which is separately determined for each standard size of a pipe and pipe material. At the stage of preheating, the melting of material is almost stopped, and its heating to the depth occurs due to its thermal conductivity.

The preheating of the mass of the pipe wall occurs nonuniformly, the lowest temperature is reached in the center, and the outer and inner surfaces of the pipe become the most heated. This is caused by the fact that not only the energy of the linear heat flux from the heater reaches the pipe surface, but also the additional heat energy from the melt squeezed into the flash and from the radiation of the heater surface. At the end of the heating stage, on the surface of each of the pipe ends, small uniform layers of viscous-flow material should be formed, which will form a welded joint at the subsequent stages [18].

The temperature of the heating tool and the preheating time are the main parameters during butt welding with a hot tool. The working area should be protected from cooling by a wind and low temperatures, and during welding under the conditions of a high temperature it is protected from the overheating and the effect of direct sunlight. The surface of the heating tool should not have scratches or other defects on the anti-adhesive coating, its temperature should be checked at different parts of the working surface. The operating temperature of the heating tool is recommended to be reduced by 5–10 % with an increase in thickness of pipes being welded [19].

In some cases, for the purpose of reducing the volume of molten material during heating, the so-called high-temperature heating tool is used, having a temperature of 100–150 °C above the melting point of the polymer [20]. In this case, to prevent the destruction of polymer, the duration of preheating is significantly reduced.

The intermediate stage of the process of butt welding with a hot tool is a technological pause t_3. During the pause, the pipe ends are disconnected from the heating tool, the latter is removed from the welding zone and the pipes are brought closer up to the contact of the end surfaces. During a pause, a heated material is cooled, it contacts with the atmosphere and can be oxidized and the flashed surfaces may contaminate with dust and moisture. Therefore, the duration of the pause is tried to be reduced as much as possible. The maximum allowable duration of the pause is set by the normative documents within 3–6 s, depending on the standard size of a pipe [5]. After the direct contact of the surfaces of the pipe ends the final stage of the process of butt welding begins: upsetting.

In the process of upsetting due to the working pressure, the physical contact of the flashed surfaces increases, which creates preconditions for the emergence of intermolecular interaction between the materials of the parts and the formation of a welded joint. Under the pressure, the squeezing out of the molten material from the welding zone and the formation of a secondary (welding) flash occur. With the flow of the melt from the weld, the pores, contaminations and other defects are removed, which could be occurred at the earlier stages of the process. The duration of the upsetting stage t_4, which determines the rate of growing the working pressure, is determined by the normative documents and grows with the increase in the thickness of the pipe wall. The excessive rate of upsetting can cause excessive stresses in the welding zone and promote the formation of defects in the welds [9] (Figure 2).

The quality of welding is largely determined by rheological processes occurring during upsetting in the zone of welded joint. It is believed that the lower the polymer's toughness, the easier it is welded. The speed of parts movement during upsetting is inversely proportional to the average toughness of the melt [21]. It is admissible to weld a pipe of different types of polyethylene, if the values of fluidity of the melts are differed little [22].

After upsetting, the last stage of a welded joint formation begins at a slow cooling of the weld while maintaining a working pressure, which lasts several minutes. The presence of pressure promotes relaxation of stresses and prevents the formation of cracks and other defects during shrinkage of material. In polymer materials, the cooling of heated regions occurs slower than in the metals, as the thermal conductivity of these materials is much lower. The heat-affected zone for the welds, which are butt welded with a hot tool, is located near the welded joint. Therefore, it is possible to control the temperature in the zone of welding by additional heating or cooling of the heat-affected zones with the use of additional tool [23]. Upon completion of the cooling stage t_5 duration, the welded joint is considered to be completely formed and removed from the welding equipment.

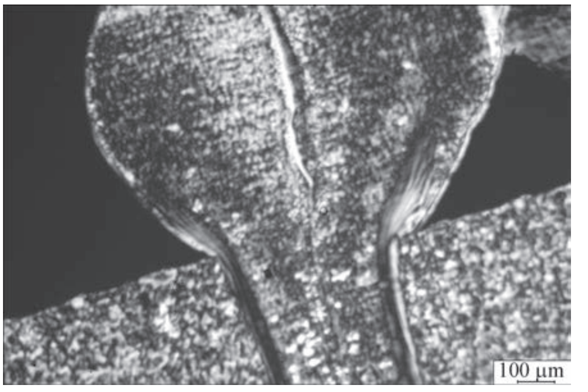

Figure 2. Defect in the form of a through crack in the welded flash and weld

It is noted that in order to provide a high quality of welds of polymer pipelines, it is necessary to strictly observe all the recommended parameters of welding process. However, even under these conditions, a coincidence is possible, which leads to defects formation in welded joints. Lack of fusion in a welded butt joint occurs when a part of the material is destroyed because of the abnormally high temperature of the heater, at overcooling of the material during the technological pause, and also because of contamination. The separate small cavities and pores inside the welds can be formed as a result of shrinkage processes, caused by nonuniform preheating of the polymer material mass (Figure 3). The impossibility of shrinkage of near-surface layers of welded joints leads to cracks formation both in the fusion area as well as in the areas under the flash along the boundary between the melt and base material [9].

One of the technological conditions for producing quality butt welds is the arrangement of a convenient workplace for welders. In practice, this principle is often violated, especially when performing different types of repair works. The typical errors are the too

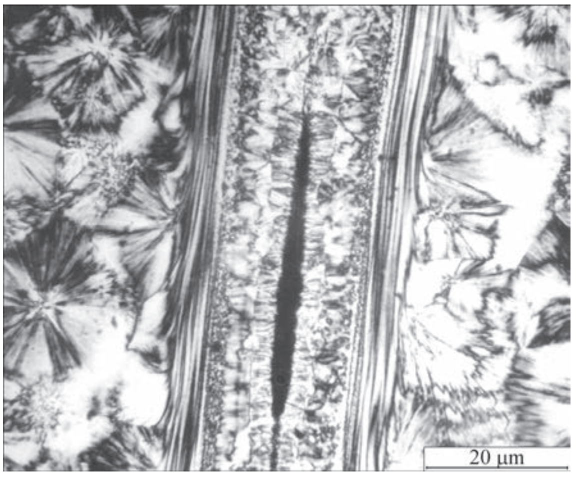

Figure 3. Defect in the form of a cavity in the weld

Figure 4. Installations for butt welding of polymer pipes using a hot tool of different European manufacturers: *a* — Georg Fischer; *b* — Widos; *c* — Rothenberger; *d* — Ritmo

small sizes of foundation pits and trenches, which do not allow a proper arrangement of assembly equipment and setting of parts to be joined. Lack of a reliable support for the aligning device, exceeding the standard time of a technological pause, can cause lack of penetrations and other defects in welds [24]. Thus, compactness, reliability and easy access are among the main requirements to the equipment intended for welding of polymer pipelines.

At present, the construction companies of Ukraine use equipment for welding polymer pipes of such leading European and Asian manufacturers, as Georg Fischer (Switzerland), Widos, Rothenberger (Germany), Ritmo (Italy), Kamitech, NowaTech (Poland), Turan Makina (Turkey), Times Asia Group Ltd. (China), etc. (Figure 4). The similar equipment is produced in the CIS countries: Russia, Belarus, Kazakhstan [25]. It should be noted that the equipment for butt welding of polymer pipes with a hot tool of all manufacturers is intended for implementation of a traditional technological welding scheme and manufactured on the same layout scheme with a hydraulic upsetting drive. For welding pipes of small diameter, small installations with a manual mechanical drive are used. The installations of different manufacturers are differed between each other only by design features and the quality of manufacture of separate assemblies and units.

An important tendency in the development of modern technology for welding of polymer pipes is the differentiation of equipment by purpose. Depending on the types of welding works, the equipment for butt welding with a hot tool can have different design solutions and different auxiliary rigging. The aligning devices of the welding installations can have different amount and capacity of the clamps, can be equipped with hydraulic, pneumatic or mechanical drives for pipes displacement. For welding in the field conditions, rigid aligning devices with four clamps are used, and the workshop machines are usually have a lightweight design and can be equipped with rotary clamps. The mutual replacement of welding installations of different purposes is generally not permitted [11]. In some cases the efficiency in the use of equipment with a pneumatic drive for butt welding of polyethylene pipes is noted, which is less expensive and its range of admissible climatic conditions is higher [26] (Figure 5).

The world tendencies in the development of technology and equipment for welding with a hot tool is its application for welding of new polymer materials, expanding of the range of operating temperatures of heaters, etc. The heating tools of «normal» temperature (up to 270 °C), elevated temperature (350–450 °C), and tools of super-high temperature of 500–

550 °C with the possibility of simultaneous heating by infra-red radiation are used [10].

The modification of the method of butt welding with a hot tool, which is called welding by displacement, is increasingly being used for welding of plane parts from polymers of different types [27, 28]. The depth of flashing at the first stage of the heating process is determined by special mechanical supports on the heating tool. Similarly, at the stage of upsetting, mechanical supports limit the relative displacement of the part ends by a preset value. Thus, the dimensions of a welded joint, formed after the weld formation, can be controlled at a great accuracy.

Despite a long historical period of using the method of welding with a hot tool and the simplicity of technology, it is considered relevant to improve and expand the application fields of this method. The traditional disadvantages of the method of butt welding with a hot tool are considered to be limited abilities to control the process and obtaining the data on its progress in real time, too long duration time of the process stages. At the moment, that welding equipment is considered to be challenging, which allows operators to perform a precise control of the movement of individual parts, the temperature of heated surfaces, and the force applied to the parts. [20].The hot tool can have different shapes, depending on the welded joint configuration. The devices for clamping of parts become interreplaceable and provide a precise alignment and maintenance of them during welding. They can function both in horizontal as well as in vertical planes. The improving of operation speed of equipment for welding with a hot tool is promoted by use of servodrives to control the displacement of parts. In order to control the basic parameters in the process of welding, such as force, speed, distance, temperature, the application of modern computer hardware and software is required.

A nonuniform distribution of temperature over the surface of a heating tool can negatively affect the final quality of a welded joint. The traditional designs of heaters usually provide the ability to control the temperature in one or two points of the working area. Some modern heating tools have up to 9 points of separate temperature programming on the surface.

The speed of displacement of parts during welding is another important parameter of the process, which affects the quality of a weld. Usually, only the rate of increase in the value of working pressure is regulated, while for the process of welded joint formation the absolute value of the displacement speed, the programmable acceleration or deceleration of movement at certain moments of time are important. The traditional welding installations have hydraulic or

Figure 5. Installation with pneumatic drives for butt welding of polymer pipes of manufacture of the E.O. Paton Electric Welding Institute of the NAS of Ukraine

pneumatic drives, which practically do not allow controlling the movement speed. The programming and control of parameters of parts movement during welding are possible with the use of modern servodrives.

Thus, a butt welding of plastic products, firstly polymer pipes, with a hot tool, was and remains one of the most widespread and popular welding methods. However, the improvement of the polymer materials themselves and the emergence of new fundamental knowledge create preconditions for simplification of welding technology, the problems of which are relevant in the modern polymer world.

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