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QUALITY AND OPERATIONAL CHARACTERISTICS OF WELDED JOINTS OF PIPES OF DIFFERENT-TYPE POLYETHYLENES

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Polyethylene raw materials used for production of polyethylene pipes are constantly being improved. At the beginning of the construction of plastic pipelines, the so-called low pressure polyethylene, currently known as PE-63 grade was used. Subsequently, new, more advanced types of raw materials, which represent a copolymer of polyethylene with hexane, were developed. Today, almost all pressure pipes are made of PE-80 and PE-100 grades of polyethylenes. However, during the repair and reconstruction of plastic pipelines, there is an urgent problem of joining pipes of PE-63, which have been operated for a long time, with new pipes made of polyethylenes of grades PE-80 and PE-100. In the paper, complex investigations of thermophysical properties of technical polyethylenes were carried out and significant differences were revealed, which should be taken into account during the repair of polymer pipelines. Experimental welding of pipe specimens from both single- as well as different-type polyethylenes was carried out. Morphological and mechanical studies of welded joints of polyethylene pipes of grades PE-63, PE-80, and PE-100 were performed. According to the results of investigations, the influence of their thermophysical properties and parameters of the welding process on the morphological structure and quality of welded joints of different-type polyethylenes was determined. Mathematical modeling of temperature fields during butt welding was carried out. A two-zone heating tool for butt welding of pipes with an outer diameter of up to 110 mm of different-type polyethylenes of pipe grades PE-63 and PE-80, PE-100 using a heated tool was designed and created. In order to test an experimental specimen of a two-zone heating tool, a series of experiments were carried out, which showed an improvement in the strength characteristics of the produced welded joints. 8 Ref., 4 Tables, 10 Figures.

Keywords: polyethylene raw material of different types, polyethylene pipes, welded joints

The problem of repairing polyethylene pipes is important in terms of their safety and reliability of operation. As is known, the old pipelines were built using polyethylene of grade PE-63, which is already technologically outdated and no longer produced, and a complete replacement of the pipeline instead of its separate section is not advisable. Therefore, to provide the repair of such pipelines, it becomes necessary to study the possibility of welding polyethylenes of different grades. In the work the results of complex thermophysical and structural investigations of polyethylenes PE-60, PE-80 and PE-100 are given. The main differences of materials were established affecting the possibility of producing a quality welded joint. Technological approaches to welding of different-type polyethylenes were developed.

At the beginning of the construction of plastic pipelines, the pipes of polyethylene of grade PE-63 were used, but with the development of the polymer industry in the 2000s, it was replaced by more technological polyethylenes of grades PE-80 and PE-100. This has led to a global problem of repair and reconstruction of old polyethylene pipes because of the need to weld materials with different thermophysical properties and the lack of available information and investigations of the quality characteristics of joints of different-type polymers, even at a short-term use. Joining parts and pipes of different grades of polyethylene have different physical and mechanical properties, and therefore require special technological parameters of their welding process. The available information on the possibilities of welding pipes and parts of polyethylene composites of different types, reliability and service life of their welded joints is significantly contradictory and limited. Some stadard documents allow welding different-type polyethylenes between each other, if they have close values of melt viscosity, which is estimated according to the value of melt flow index. However, the problem of optimizing the process of welding heterogeneous polyethylene pipes is not easy and requires additional investigations and appropriate adaptation of welding equipment [1]. While choosing the parameters of the process of welding polyethylene pipes, it is necessary

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Table 1. Characteristic temperatures of thermal oxidative destruction of specimens of technical polyethylenes PE-63, PE-80 and PE-100

Specimen	T_d, °C	$T_{d\,max}$, °C
PE-63	252	418
PE-80	264	420
PE-100	274	450

to take into account the peculiarities of the thermophysical properties of the base material, as well as the presence and amount of impurities. In particular, the material of pipes that have already been in operation may have impurities that have appeared as a result of adsorption from the environment [2].

Materials and procedures of investigations. To perform welding works, as the model objects, polymer pipes with a nominal outer diameter of 63 mm and a wall thickness of 5.8 mm were used, made of three grades of technical HDPE with a different minimum long-term strength MRS, namely PE-63 (density is 0.940 g/cm^3, MRS6.3 according to GOST 16338 [3], GOST R 50838 «Polyethylene pipes for the supply of gaseous fuels» [4]), PE-80 (density is 0.941 g/cm^3, MRS8 MPa) and PE-100 (density is 0.954 g/cm^3, MRS10 MPa) [5, 6].

At the first stage, the thermophysical properties of the polymer material of polyethylene pipes of all three grades were investigated applying differential scanning calorimetry (DSC) in the calorimeter TA Instruments DSC Q2000 and applying thermomechanical analysis (TMA) in the device TA Instruments TMA Q400 EM.

At the second stage, experimental welding of polymer pipes, both single-type as well as those of different grades, was performed using «butt» method with a heated tool according to the conventional flowchart (Figure 1). The parameters of the welding mode were set according to the requirements of the standard [7] – temperature of the heated tool is 210 °C, heating time is 60 s, technological pause is 3 s, upsetting pressure is 0.2 MPa, cooling time under pressure is 6 min.

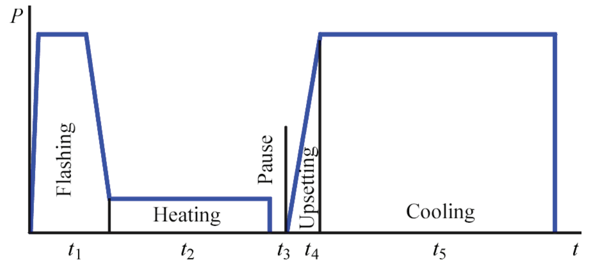

Figure 1. Flowchart of conventional process of butt welding using heated tool

At the third stage, the produced welded joints of single- and different-type polymer pipes in different combinations were laid in an environment that simulates the operating conditions — into the ground to a depth of 10 cm, and on the surface, where they were under the influence of climatic factors during 1 and 2 years.

At the fourth stage, comprehensive investigations were carried out to study the long-term effect of the environment on the experimental specimens. The structural features of the specimens were investigated by means of wide-angle X-ray scattering (WAXS in the X-ray diffractometer DRON-4-07) and optical microscopy in the Versamet-2 microscope. The service characteristics of polymer pipe welds were evaluated applying the methods of visual inspection in accordance with DSTU EN13100-1:2017 and mechanical tensile tests in the rupture machine FP-10 in accordance with DSTU EN12814-2:2018 and DBN V.2.5-41.

Thermal processes during welding of pipes of different-type polyethylenes were theoretically investigated applying mathematical modeling using the finite element method.

Results of thermophysical studies. Thermogravimetric analysis (TGA) of the specimens of technical polyethylenes showed that as to the character of TGA curves (Figure 2, *a*), polyethylenes of all three types are similar, however, the temperature of the beginning of thermal oxidative destruction of polyethylene PE-63 is lower as compared to PE-80 and PE-100 (Table 1). The rate of thermal oxidative destruction of polyethylene

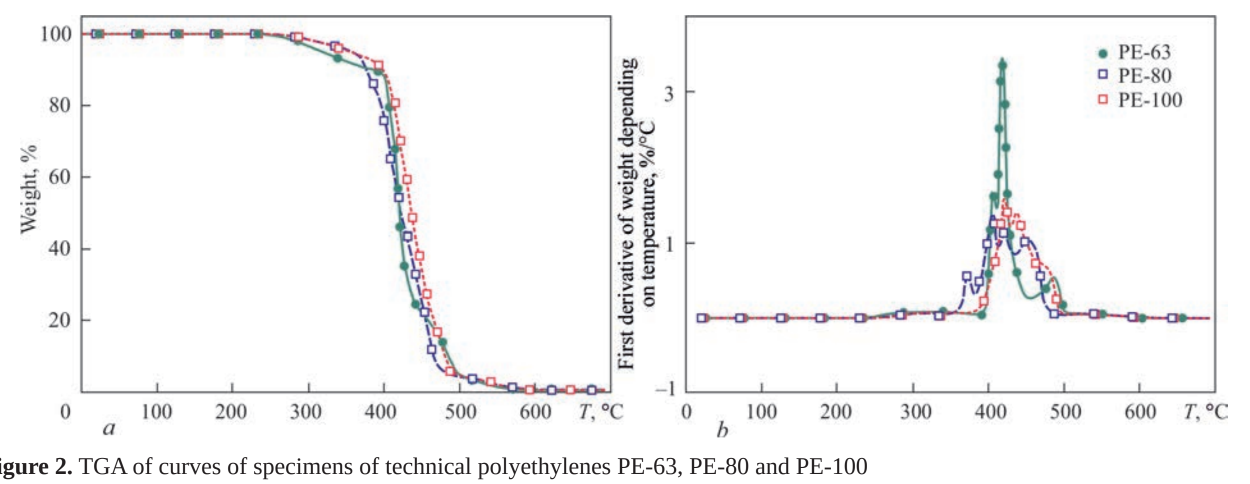

Figure 2. TGA of curves of specimens of technical polyethylenes PE-63, PE-80 and PE-100

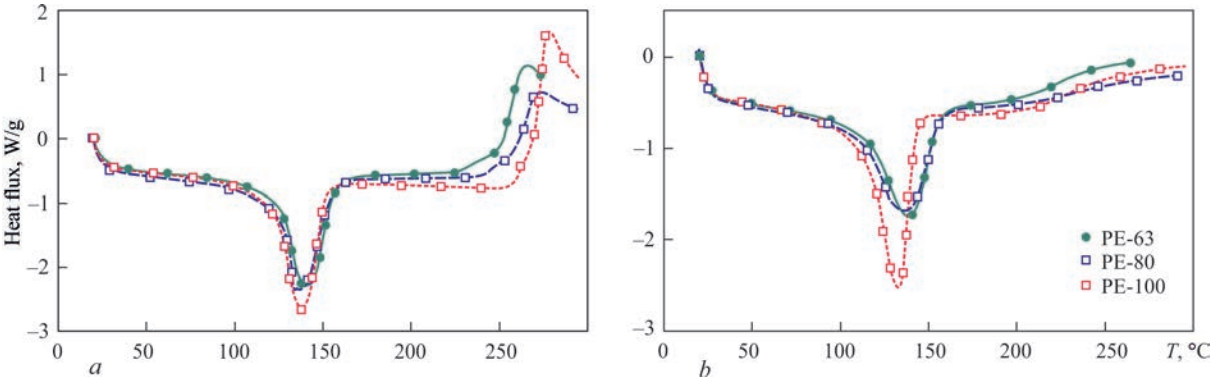

Figure 3. DSC curves of specimens of pipe polyethylene grades PE-63, PE-80 and PE-100 during the first (*a*) and second (*b*) heating

PE-63 is much higher (Figure 2, *b*) at a temperature of intensity maximum $T_{d.max} \approx 418$ °C as compared to PE-80 and PE-100 at the temperatures of intensity maxima $T_{d.max.} \approx 420$ and 450 °C, respectively.

The corresponding curves were obtained applying the DSC method for the specimens of technical polyethylenes PE-63, PE-80 and PE-100 during the first (Figure 3, *a*) and second (Figure 3, *b*) heating. During the first heating, exothermic processes on the curves at a region of about 250 °C are seen, which are absent during the second heating, which may be associated with thermal relaxation of stresses remaining in the polymer after pipe formation or during a final polymerization of polyethylenes. During the second heating, the change in the character of maxima of endothermic processes in the region of temperatures of 130–140 °C is observed. Therefore, melting of polyethylenes, shift of their temperatures and a decrease in enthalpy occurs during the first heating.

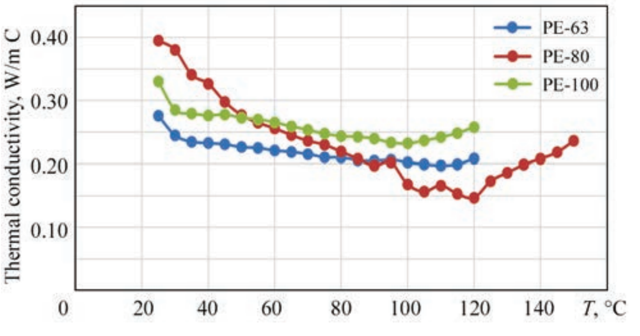

Figure 4. Thermal conductivity of technical polyethylenes PE-63, PE-80 and PE-100

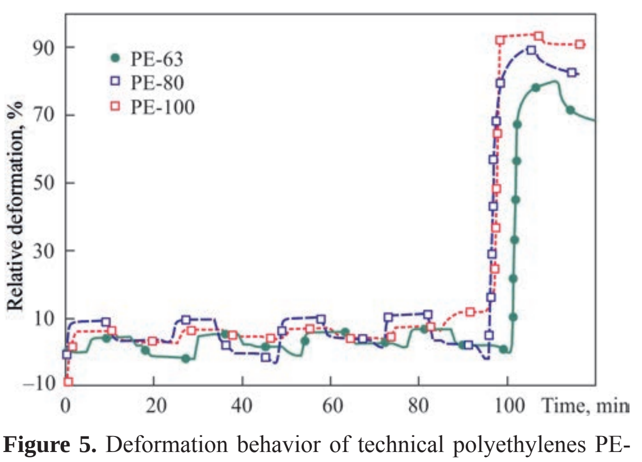

Figure 5. Deformation behavior of technical polyethylenes PE-63, PE-80 and PE-100

It should be noted that DSC curves of the first and second heating and characteristic thermophysical parameters of melting (Table 2) differ in some way for all three grades of technical polyethylenes.

The comparison of the thermal conductivity curves (Figure 4) shows that this parameter for all three grades of polyethylenes both according to isothermal values as well as with the changes in temperatures can differ in several times, which can not but affect the melting processes during welding.

The creep and stress relaxation curves of the specimens of three grades of polyethylenes at different temperatures were also compared (Figure 5). If at the temperatures much lower than the melting point of individual polyethylenes the isothermal deformation curves of polyethylenes during creep and stress relaxation are similar, then with an approach to the melting point their behavior differs significantly. For the specimen of polyethylene PE-63, the deformation values are the lowest, which is probably connected with its high viscosity, and the specimen of PE-100 is deformed as an already low-viscosity melt.

Thus, the carried out investigations showed significant differences in the thermophysical characteristics of technical polyethylenes, especially between the polyethylene of grade PE-63 and the polyethylenes

Table 2. Characteristic thermophysical parameters of melting specimens of pipe polyethylenes PE-63, PE-80 and PE-100

Specimen	T_m, °C	Δ*H*, J/g
1st heating		
PE-63	141.3	112.0
PE-80	136.9	116.1
PE-100	137.6	120.9
2nd heating		
PE-63	138.9	93.5
PE-80	137.5	95.6
PE-100	133.0	112.3

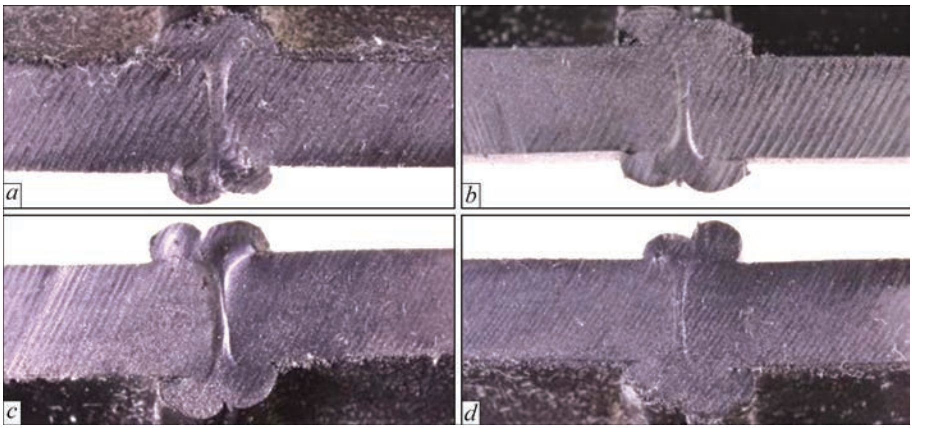

Figure 6. Morphology of welded joints of polymer pipes of different- and single-type polyethylenes: *a* — PE-63/PE-63; *b* — PE-100/PE-100; *c* — PE-100/PE-63; *d* — PE-63/PE-80

of grades PE-80 and PE-100. These differences, of course, should be taken into account while welding pipes of different grades of polyethylene. However, the flowchart of the conventional method of butt welding of polymer pipes using a heated tool does not take into account these features.

Results of investigations of experimental welds. In a year after laying into the experimental environment, a study of the morphology and mechanical characteristics of experimental welded joints was carried out. Sections of welds of pipes from the single- and different-type polyethylenes are presented in Figure 6.

There was a significant difference in the shape and volume of the welded flash was revealed in the welded joints on the side of different-type polyethylenes (Figure 6, *c*, *d*) as compared to the welded joints of single-type polyethylenes (Figure 6, *a*, *b*). It is important to note that according to the valid standards [7], the flash of such shape is characteristic of poor quality welded joints, and the welded joint itself is considered to be unsuitable for use. According to the valid standards for a high-quality weld, the flash beads on both sides of the welding plane should have the same shape and volume, as is seen in welded joints of pipes of single-type polyethylenes. In the case of welded joints of pipes of different-type polyethylenes, a nonuniformly distributed flash is observed on both sides of the welding plane, and therefore, such welded joints may be considered as poor. The difference in the shape and volume of the flash for different-type welded joints is predetermined by the difference in their thermophysical characteristics, which was shown above.

The structure and properties of welded joints of pipes of different-type polyethylenes, which for 2 years were exposed to the action of climatic factors, were studied using an X-ray diffractometer. The analysis of wide-angle X-ray diffraction patterns of the specimens of welded joints PE-63/PE-100, which were in the air and on the ground showed that they all have an amorphous-crystalline structure, which is indicated by the presence of diffraction maxima at $2\theta_{max}$ = 21.2 and 23.6 against the background of an imaginary amorphous halo with an apix at $2\theta_{max} \approx 21.0°$ (Figure 7).

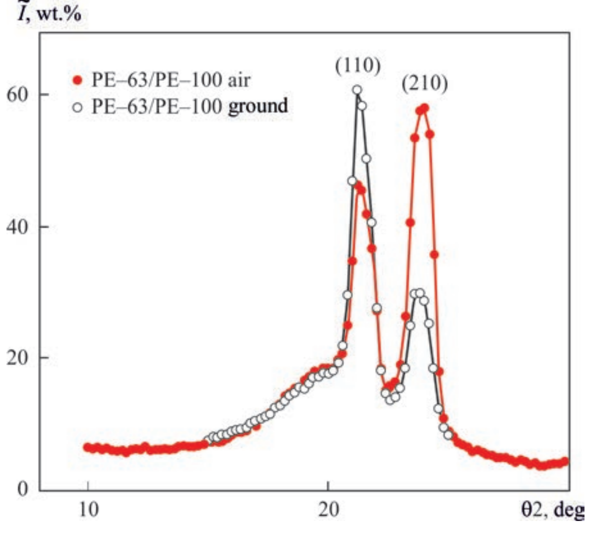

Figure 7. Wide-angle X-ray diffraction patterns of welded joints of polyethylenes PE-63/PE-100, which were in the air and on the ground

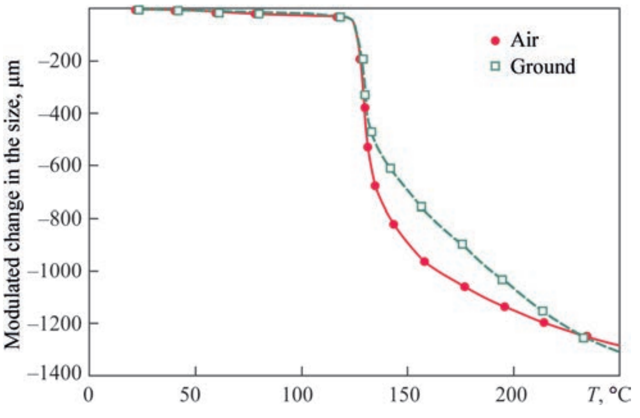

Figure 8. Modulated change of the size of specimens of welded joints of PE-63/PE-100, which were under the influence of factors of the operating environment, on temperature

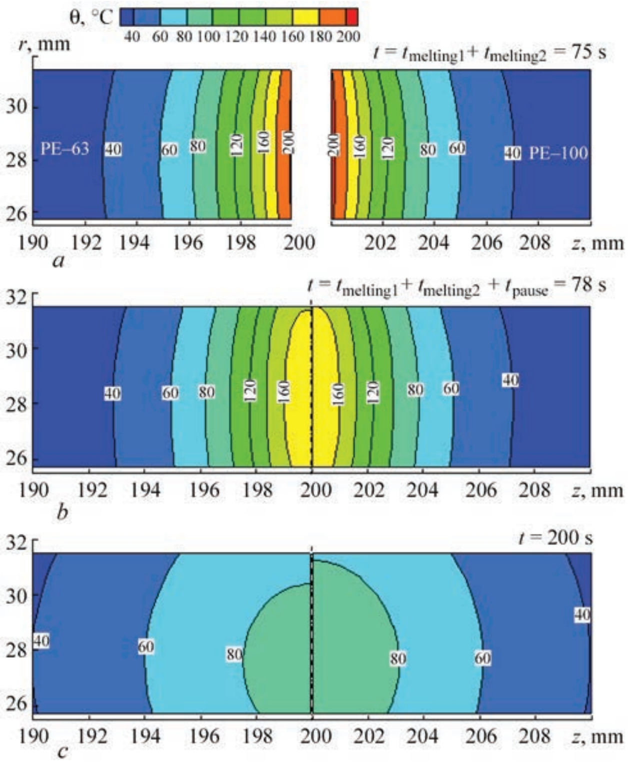

Figure 9. Isolines of temperature field at different time points during butt welding of pipes PE-63/PE-100 (see description *a*–*c* in the text)

It is noteworthy that for the welded joints of PE-63/PE-100, which were in the air under the action of ultraviolet radiation, a change in the intensity of diffraction maxima in the planes (110) and (200) occurs, which indicates significant changes in the structure of the welded joint material. During the analysis of wide-angle X-ray diffraction patterns of the specimens of welded joints of PE-63/PE-63 and PE-63/PE-80, which were in the air and on the ground, significant changes in their structure organization were not revealed.

Figure 8 shows the curves of the modulated change in the size of the specimens of welded joints of PE-63/PE-100, respectively, which were exposed to the influence of factors of the working environment, from temperature.

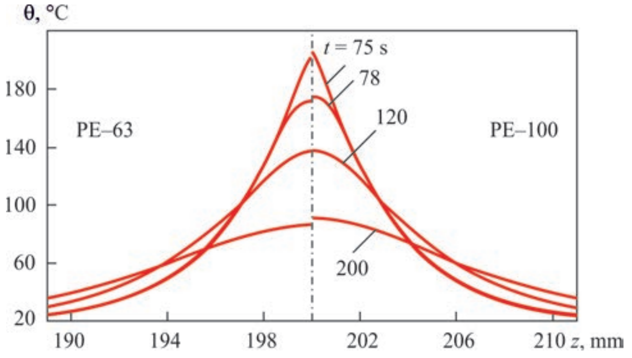

Figure 10. Temperature distribution along the midline for different time points during butt welding of pipes PE-63/PE-100

With the exception of an increase in the value of thermal expansion before melting of the crystalline phase of polyethylenes in the specimen of welded joint of PE-63/PE-80, which was on the surface, and a somewhat sharp process of melting the specimen of welded joint of PE-63/PE-80, which was on the ground, a significant difference between the behavior of the thermomechanical curves of both specimens is not observed. This is most likely explained by the absence of significant changes in the structure of both welds. A completely different situation is observed for the specimens of welded joints of PE-63/PE-100. The curves of the modulated change in the size of the specimens of welded joints of PE-63/PE-100, which were exposed to the influence of factors of the working environment, on temperature namely on the surface and on the ground, have a significant difference in the region of melting crystalline phase of polyethylenes. This can certainly be explained by the change in the structure of the crystalline phase of polyethylenes in the weld, which is confirmed by the results of X-ray structural examinations, which are shown in Figure 9.

The service properties of welded joints were studied in the course of mechanical tests in the mode of uniaxial tension (Table 3). It is seen that welded joints of PE-63/PE-80 has the most significant effect on the deterioration of mechanical properties, regardless of the environment. However, it should be noted that the specimens in the ground underwent the major changes in mechanical strength. This is probably associated with the lack of action of ultraviolet radiation, which, as is known, firstly leads to the cross-linking of polyethylene, accompanied by an increase in its strength, against the background of its aging, which to some extent, as is seen from Table, is typical for all specimens.

Results of mathematical modeling of temperature fields. In order to evaluate the influence of the difference in thermophysical characteristics of the material on the process of welding different-type polyethylenes, mathematical modeling of temperature fields was performed during the welding process.

Figure 9 shows the isolines of the temperature field at three moments of the butt welding process: *a* — at the beginning of the technological pause of 75 s;

Table 3. Change in mechanical strength of welded joints specimens over time

Specimen	PE-63 1 year/2 years	PE-80 1 year/2 years	PE-100 1 year/2 years
Ground			
PE-63	19.38/19.68	18.76/18.03	19.69/18.79
Air			
PE-63	19.23/19.48	17.84/16.5	19.53/19.55

Table 4. Recommended temperature of operating surfaces of double zone heater during welding of different-type polyethylenes

Temperature of surrounding air, °C	Combinations type of polyethylenes					
	PE-63	PE-80	PE-63	PE-100	PE-80	PE-100
–10–0	230	220	220	230	220	230
0–20	220	210	210	220	210	220
20–45	210	200	200	210	200	210

b — at the time of joining of the ends and the beginning of compression of the pipes during upsetting; *c* — approximately in the middle of cooling duration. Because to differences in the thermophysical properties of polyethylenes on different sides of the pipe butt joint, nonuniform thermal fields are formed. In Figure 10 a gradual equalization of temperature in the middle side surface of the pipe is seen.

Designing and testing of two-zone heating tool. The abovementioned investigations of the difference in properties of technical polyethylenes PE-63, PE-80 and PE-100 showed that the use of the conventional scheme of butt welding of different-type pipe polyethylenes using a single-zone heated tool leads to a technologically incorrect weld formation, which according to the nature of the welding process and the appearance of the welded flash does not meet the valid building standards, and therefore a need appeared to create special equipment to provide a quality welded joint during butt welding using a heated tool. To solve the problem of increasing the efficiency of repair and extending the life of plastic pipelines, in the course of the work, a two-zone heating tool for butt welding of pipes with an outer diameter of 110 mm from different-type polyethylenes of pipe grades PE-63 and PE-80, PE-100 using a heated tool was designed and created.

At a regulated heating at different temperature, on the surfaces of a two-zone heater on the ends of pipes on both sides the same quantity of melt is formed, during upsetting the symmetrical weld with the identical sizes of beads of a flash around the whole orbit of a butt is formed.

The conclusion about the mechanical strength of the weld of different-type polyethylene pipes, produced with the help of a two-zone heating tool, is provided by destructive tensile tests of the specimens carried out in accordance with the requirements of the standard DSTU EN12814-2: 2018 [8].

The fracture of the specimens had the similar plastic nature. During plastic deformation of the specimen, the «neck» was formed in the region of the fusion line and propagated towards the less strength polymeric material. The maximum tensile load for the specimen of PE-80/PE-63 (No.1), welded using the conventional technology, was 710 N, and for the specimen of PE-80/PE-63 (No. 2), welded using the two-zone heated tool, was 880 N. After the corresponding calculations, the yield strength value of the polymeric material was obtained — 25.8 MPa for the specimen No.1 and 29.4 MPa for the specimen No.2. Thus, the strength of the welded joint of different-type polyethylene pipes welded applying the new technology appears to be by 15 % higher. Since the specimens with a narrowed working part were tested, in this case the strength of the weld material was determined. According to the results of experimental studies, the recommended values of temperature on the surfaces of the two-zone heating tool in different environmental conditions were determined (Table 4).

Conclusions

In the work the influence of heterogeneity of polyethylenes on the process of their welded joint formation was investigated. The solution to the problem of welding pipes from different-type polyethylenes applying the two-zone heating tool for butt welding using the heated tool created within the framework of this study is given. The technological approaches were developed, that allow producing high-quality welded joints of different-type polyethylenes.

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