MECHANICAL QUALITY OF WELDS IN POLYETHYLENE PIPE SYSTEMS

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The weld strength of some butt welds and extrusion welds in pipeline systems, made of the newer PE types, has been evaluated by means of short-term and long-term tests. Butt welding appears to be a reliable jointing method. Welding strength is almost independent of the heating plate temperature and welding pressure. A suitable non-destructive testing (NDT) method is not available. Careful extrusion welding also gives a good weld quality.

INTRODUCTION

For the distribution of water, gas and heat polyethylene (PE) pipelines are often used. These pipes are connected by various welding techniques, like butt welding, socket welding, electrosocket welding and extrusion welding.

Basically the welds can be considered as the most vulnerable parts of the pipeline system. To guarantee a safe and reliable use of these pipeline systems, the welds therefore should be made carefully and under the right conditions.

Many papers about welding of PE pipes have already been published and welding specifications set up. Yet all questions have not been fully answered and new questions arise, like welding compatibility.

In this paper attention will be paid to two problems regarding welding of PE pipes. The main part of the paper will deal with butt welds in PE gas distribution pipelines. Butt welds in such pipes have been evaluated extensively in the past, but these studies were limited to rather old PE types. It is questioned now if the welding specifications, set up for these older PE types, also hold for the newer PE types which are on the market now.

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For this purpose a renewed evaluation of the butt welding process has been started, on which the present paper reports.

The second subject of this paper is the quality of extrusion welds. Extrusion welding is a relatively new jointing technique used for instance to connect casing pipes in district heating systems.
In this paper some results of a preliminary investigation into the strength of extrusion welds will be presented.

BUTT WELDING

Introduction: the butt fusion welding process

The process is basically simple: the faces to be joined are brought up to a heating plate and heated for some time, the plate is withdrawn and the two faces are then pressed together. A small bead will form on the inside and outside surfaces and this will give us some indication of the weld quality.

In the butt welding process 4 different stages can be distinguished:

1. Preparation of the surfaces to be welded.
2. Heating of the ends to be connected by welding.
   Usually the heating is carried out in two steps.
   During the first stage the pipe ends are brought up to the heating plate under a certain pressure and held there until a bead of a certain size has formed. This heating stage under pressure is followed by a non-pressurized heating period.
3. The removal of the heating plate.
4. The welding and cooling under pressure.

Thus the complete butt welding process can be described by the following welding parameters:

T_1, the heating plate temperature (welding temperature)
t_1, the heating time under pressure
t_2, the heating time with no pressure applied
t_3, the change-over time of the heating plate
p_1, the heating pressure
p_2, the welding pressure
t_4, the welding time under welding pressure.

Though the butt fusion process is basically a simple process, many combinations of welding parameters are possible, so establishing the allowable range of welding conditions is a laborious task.

The investigations reported here are therefore restricted to some variations to the established butt welding procedure in Holland, the so-called NIL-specification (1). In this NIL-specification the heating plate temperature, T_1, is fixed at 205 ± 8 °C. The heating pressure p_1, is restricted to 0.075-0.20 MPa, and the welding pressure p_2 is kept between 0.15 and 0.20 MPa. The other welding parameters depend on the pipe dimensions. For the Ø 160 x 9.1 mm pipes, on which most of our experiments were performed, these parameters were: t_2 = 2 min.; t_3 = 3 sec.; t_4 = 13 min.; t_1 = the time up to the formation of a bead of 1.5 mm.

In the experiments performed here the welding temperature T_1 (180 - 260 °C), heating pressure p_1 (0.05 - 0.7 MPa) and welding pressure, p_2 (0.05 - 0.7 MPa) were varied. All other parameters were held constant.

In all our experiments the size of the final weld bead remained within the requirements set by NIL (1), i.e. the bead width was between 8 and 11 mm for the Ø 160 x 9.1 mm pipes.

The butt welds were made with a Fusion Equipment Ltd. hydraulic welding machine using a teflon-coated heating plate.

Welds were made from three different commercially available PE pipes. The density and melt flow index of these materials are given in Table 1. Only pipes of the same material were welded to each other.

TABLE 1 - Density and MFI (190 °C/5 kg) of the PE types used

Material	Density (g/cm^3)	MFI (g/10 min)
A	0.958	0.49
B	0.954	0.42
C	0.940	1.14

Weld strength

The quality of the butt welds has been characterized by means of short-term (tensile test, tensile impact test) and long-term (internal water pressure test, static load test) tests.

Tensile test. DeCourcy and Atkinson (2) have reported results of tensile tests on test pieces taken axially from butt welds For welds made at a certain range of conditions complete yielding over the whole test piece was found. Welds made at other welding conditions, however, showed fracture in the weld zone and limited yield behaviour. The elongation at break of the test specimen, therefore, appeared to depend on the welding conditions.

From the welds we made, test samples were taken in axial direction (weld bead removed as well as left on) and tested at a speed of 100 mm/min.
It appeared that in almost all tensile tests yielding started away from the weld, but did not pass the weld zone. Hence, short-term weld strength exceeds the yield strength of the material. However, yielding was always limited to part of the sample. It was not possible to make a distinction between welds made at various conditions. In our opinion, it is therefore impossible to optimize welding conditions by means of tensile testing. Only very bad welds will break below the yield strength.

The difference in tensile testing behaviour observed by DeCourcy and Atkinson (2) on the one hand and the present authors on the other hand may be caused by the tensile test speed used.

We used a speed of 100 mm/min, whereas DeCourcy and Atkinson tested at a speed of 50 mm/min.
This is now being further investigated.

Tensile impact strength. Before tensile impact testing the weld bead was removed carefully. It was found that tensile impact strength is almost independent of the welding conditions.

Internal water pressure tests. These tests were performed at 80°C at hoop stresses of 5, 4 and 3 MPa.
In these tests only pipe failures have been found; no failure occurred in the weld region.

The occurrence of failure in the pipe and not in the weld region is in accordance with expectation because in this test the tangential wall stress is two times that of the axial wall stress. Only very bad welds will lead to premature failure in the weld zone during these tests.

Static load tests. Specimens taken axially from butt welds were statically loaded in water at 80 °C or in a solution of a 5% detergent (Antarox CO 630) in water at 80 °C. These tests in detergents have been performed to accelerate the failure processes. The tests were performed at various stress levels until failure occurred.

In most of these tests failure occurred in the weld zone. The welding conditions did not significantly affect failure time (Table 2).

TABLE 2 - Static load test results (at 80 °C in a detergent) of butt welds made at various welding conditions (material A)

Welding parameters			Average failure time (hrs)		
T_1 (°C)	p_1 (MPa)	p_2 (MPa)	at 5 MPa	at 4 MPa	at 3 MPa
180	0.13	0.13	22	61	> 537
180	0.72	0.72	25	82	465
200	0.20	0.20	36	49	-
220	0.13	0.13	15	48	274
220	0.15	0.15	22	92	-
220	0.72	0.72	20	76	743
260	0.13	0.13	16	-	-
260	0.72	0.72	17	48	-

Comparison of the strength of welded and unwelded material (Fig. 1) shows that failure time for welded pipes is almost equal to that of unwelded material (at the same stress level).

In the same Figure the effect of the detergent on failure time is given, which shows that failure time in water is about 10 times that in the detergent.

Summarizing, the weld strength of butt welds made at a rather broad range of welding conditions is good and almost independent of the welding parameters used.
Hence, it may be concluded that butt welding is a reliable jointing method.

In support of this conclusion, however, more evidence should be presented. This will be given in the next paragraphs which report about some temperature and welding displacement experiments during butt welding.

Measurements during butt welding

Welding displacement experiments. During welding the displacement of the two pipe ends as a function of time was measured. This displacement is connected with the weld bead formation.

To make interpretation of the displacement results more easy the different stages of the butt welding process are given schematically in Fig. 2.

For a certain set of welding parameters (T_1 = 200 °C, $p_1 = p_2$ = 0.18 MPa) the results of these measurements are presented in Fig. 3. These results show that the displacement during the pre-heating stage, which lasted about 45 sec., is about 0.4 mm for each pipe end. During the final fusion process a welding displacement of an additional 2.5 mm for each pipe end occurred.
The displacement during the final fusion process occurred for the main part in a very short time interval; in only 6 seconds a displacement of 2.1 mm occurred.
Afterwards only a gradual and small displacement took place which can be ascribed partly to thermal shrinkage effects.

Welding displacement, i.e. weld bead formation, depends on the welding pressure. But above a certain threshold pressure, welding displacement is independent of welding pressure (Fig. 4). Apparently the flow of melted material into the weld bead is only affected when rather low pressures are used. At these low pressures the rate of flow is rather low, causing the flow process to last relatively long (30 seconds or more). During this time the resistance to flow increases by cooling effects of the material. Therefore only part of the originally melted material will be pushed into the bead. At the higher pressures the rate of flow is high and almost unaffected by pressure. All melted material is then pressed into the weld bead within a few seconds. Cooling effects during this fast flow process have no influence on the total displacement obtained.

Welding displacement also depends on the heating plate temperature. At higher plate temperatures the welding displacement is greater, i.e. the weld bead will be larger. This higher welding displacement at higher heating plate temperatures is caused by a thicker layer being melted during the heating stage. This melted layer is completely pushed into the weld bead.

Though the three materials differ considerably in MFI, only rather small differences in final welding displacement were observed (Fig. 5). MFI apparently has no influence on the final welding displacement obtained; it only affects the welding displacement rate.

Temperature measurements. By means of very small thermocouples placed at different spots in the pipe wall the temperature as a function of time was measured during welding.

In Fig. 3 the results of such a measurement for a thermocouple which is placed in the middle of the pipe wall on the pipe end is given. The thermocouple stayed on this spot during the complete welding process.
Butt welding was performed under the same welding conditions as given above.

The measured heating plate temperature was 200 °C. After the heating period the material had a temperature of about 187 °C. In the change-over time of the heating mirror, which is about 3 seconds, the temperature of the pipe end decreases to 170 °C. During the first 10 seconds of the final fusion period under pressure this temperature falls rather steeply.
At the same time a rather large weld bead is formed (Fig. 3).
Fusion of the pipe ends will probably take place after the displacement of the pipe ends is almost finished.
From Fig. 3 it can be seen that this displacement is almost finished after a real welding time of 20 seconds.
In these 20 seconds the temperature falls to about 120 °C. This means that the temperature of the final fusion surface is about 120 °C. After the end of the complete welding period, when the pressure is released, the final fusion surface still has a rather high temperature of about 60 °C.

Temperature measurements at various distances from the pipe ends showed that a layer of approximately 2.5 mm is heated up to above 120 °C during the heating period (Fig. 6).
In the final welding-under-pressure stage the melted material in this layer flows into the weld bead.

Other measurements at various welding conditions showed that in all cases main displacement took place in a rather short time (5 - 40 sec.). This means that the weld bead is formed rather quickly. Just after this fast formation of the weld bead the temperature of the final fusion surface is about 120 - 125 °C, which is about equal to the melting temperature of polyethylene.

Hence, the temperature of the final fusion surface is largely independent of the heating plate temperature and welding pressure and clearly lower than the heating plate temperature.

Discussion about weld strength

From literature (Potente and Reinke (3)) it is known that the weld strength is determined by diffusion processes over the final fusion surface as well as by flow processes in the fusion region.

From our displacement and temperature measurements it appears that diffusion over the final fusion interface takes place at temperatures which are almost independent of heating plate temperature and welding pressure. So the contribution of diffusion to weld strength is expected to be quite the same for all welding conditions.

Flow in the fusion region probably is also almost equal under all welding conditions tested. Only in the weld beads differences between various welding conditions may be expected. The hot, melted material is always pushed into the weld beads.

Hence, it may be expected that weld strength is almost independent of welding conditions. This expectation is indeed confirmed by the results of our short-term and long-term strength determinations.

Butt welding therefore can be considered as a kind of self-correcting process. Differences in heating mirror temperature (180-260 °C) and welding pressure (0.05-0.7 MPa) only affect the weld bead formation, but the final weld quality is independent of these welding parameters.

Non-destructive testing

Though reliable butt welds can be made at a rather broad range of welding conditions it is still possible that bad welds are obtained in practice. A too low welding pressure, over the complete welding period, for instance, results in void formation in the weld zone, by which mechanical strength is strongly reduced. An NDT method therefore is very attractive.

In principle, three methods are available, visual inspection, X-ray radiography and ultrasonic (US) testing.

Visual inspection is very valuable and some welding faults, like misalignment, are detected. However, a visually good weld does not guarantee a good mechanical quality.

The possibilities and limitations of X-ray and US-testing have already been described in literature (Herrmann (4)). The last years, however, these methods have been improved. Therefore, these NDT methods have been evaluated once more by testing both good and intentionally badly made welds.
It appeared that rather large defects, like inclusions, voids, etc. can be detected by careful X-ray and US-testing.
These welds also have a poor mechanical strength.
So, if defects are detected by X-ray or US-testing the mechanical quality is doubtful. Unfortunately, however, the reverse is not true. If no defects are found, this does not mean that the mechanical weld quality is satisfactory. In certain welds, so-called cold fusion welds, no defects are detected, whereas the mechanical strength (tensile test, static load test) is still very poor. Cold fusion produces a planar rather than a volume defect.

To control butt weld quality it is therefore necessary to use good welding equipment, to work strictly according to the specifications and to have well-trained welders. It is recommended that the heating plate temperature and the pressure be recorded as a function of time during welding by the incorporation of suitable equipment in the welding machine.

In conclusion, butt welding is a reliable jointing process. The quality of the butt welds is rather independent of heating plate temperature and welding pressure.
Nevertheless the welding specifications should be strictly observed, because a 100% safe NDT method does not exist.

EXTRUSION WELDING

In extrusion welding hot, melted material is brought from outside into a V-shaped opening between the two pipe ends. Various parameters can be varied in this welding process, like temperature of the supply material, heating temperature of the V-shaped surfaces of the pipe ends, geometry of the V-shaped opening, etc.

In a preliminary investigation some of these parameters were changed and the resulting welds tested by means of short-term testing methods (bending test, Charpy impact test, tensile test). If the welding conditions were not carefully selected short-term mechanical behaviour was poor (often poor welding resulted in the presence of notches in the root of the weld).

By means of these short-term tests the welding conditions were chosen in such a way that short-term behaviour was satisfactory. Welds made at this set of welding conditions were then tested by long-term static loading at 80 °C in a 5% detergent (Antarox CO 630) in water. The results of these tests are shown in Fig. 7. Results of butt welds made from the same material are also included. It can be seen that the long-term weld quality of a carefully made extrusion weld is rather good, though clearly less than that of butt welds.

Extrusion welding therefore also can be considered as a reliable jointing method, provided that welding is performed in a careful way.

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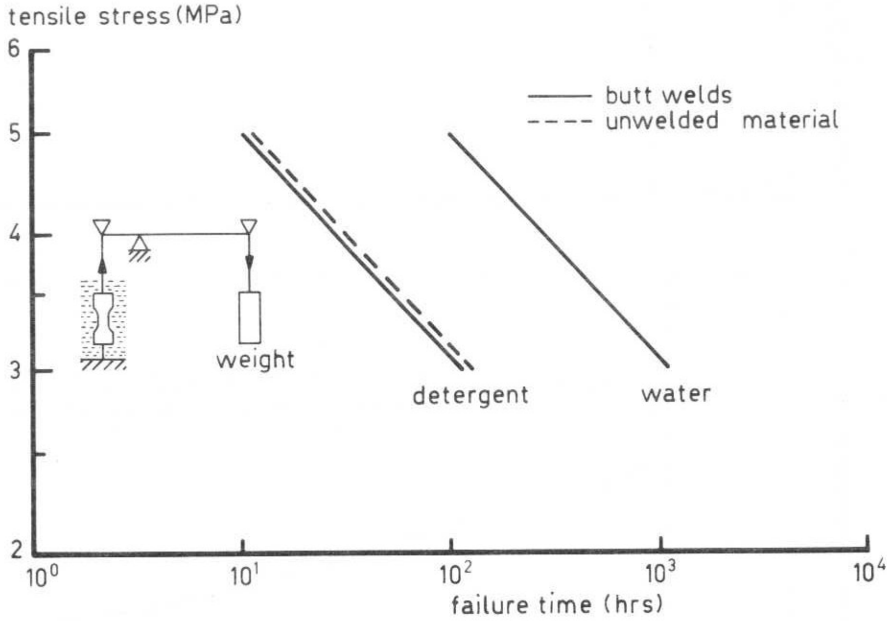

Figure 1 Static load test results (80 °C) of butt welds from material A (minimum failure lines).

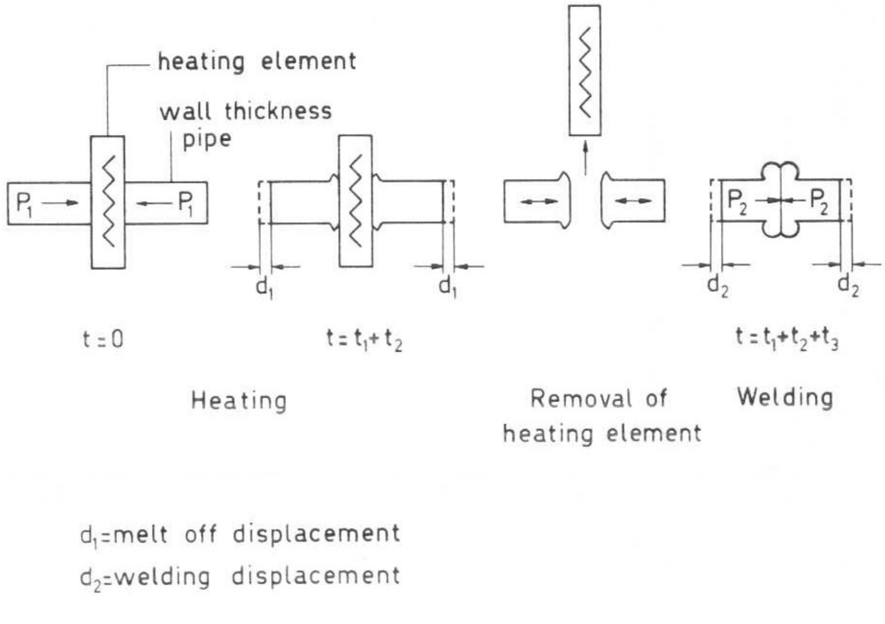

Figure 2 Different stages in the butt welding process.

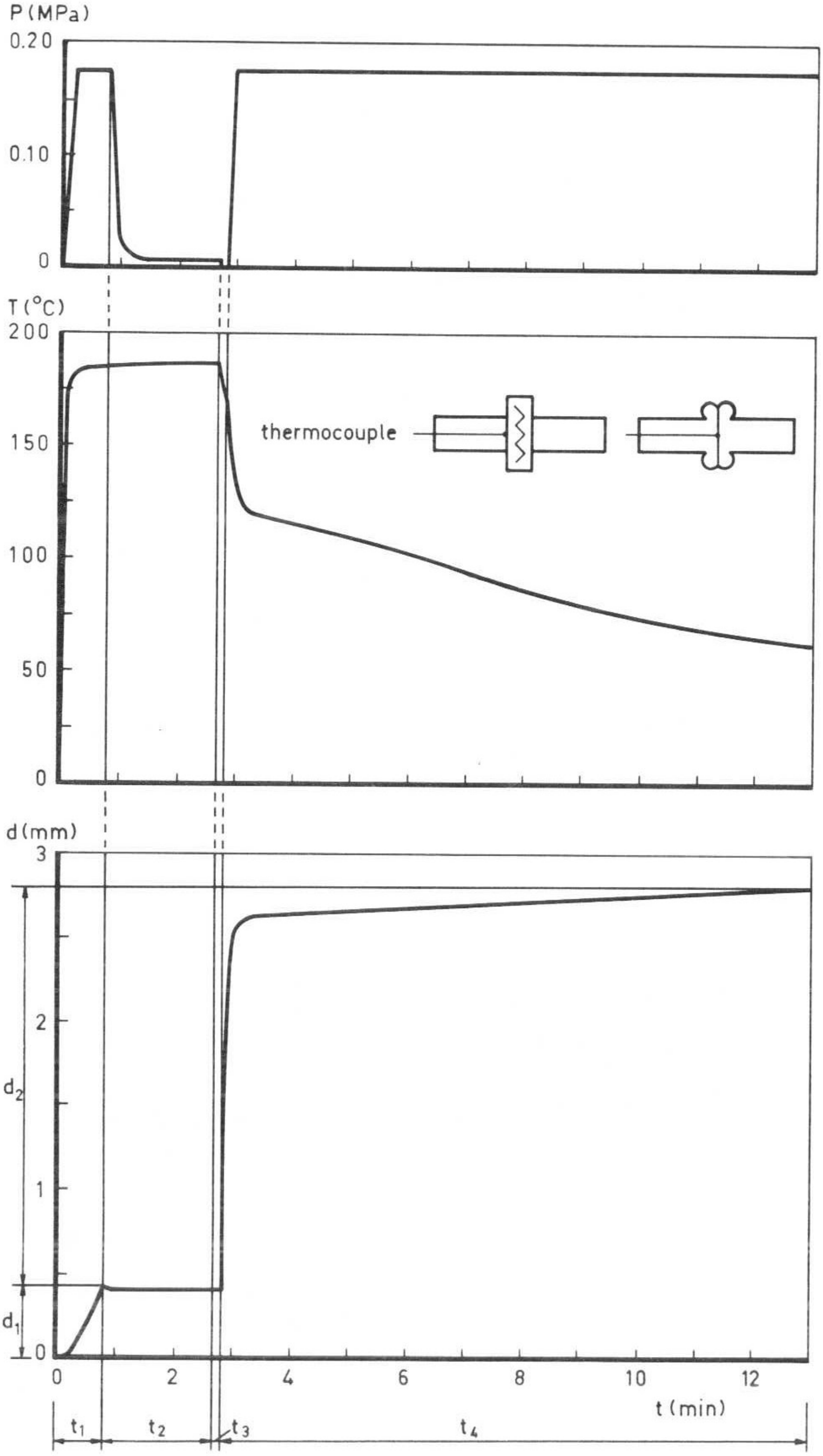

Figure 3 Pressure, displacement and temperature as a function of time during the butt welding process (material B).

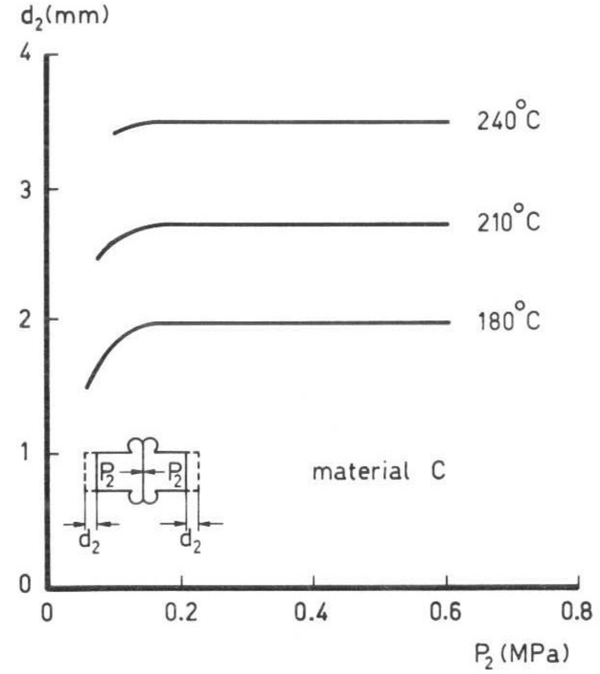

Figure 4 Welding displacement versus welding pressure

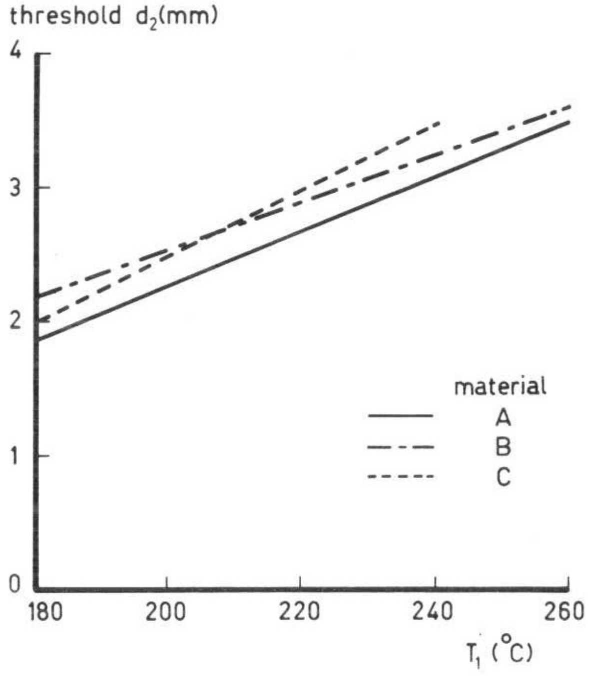

Figure 5 Welding displacement versus heating plate temperature

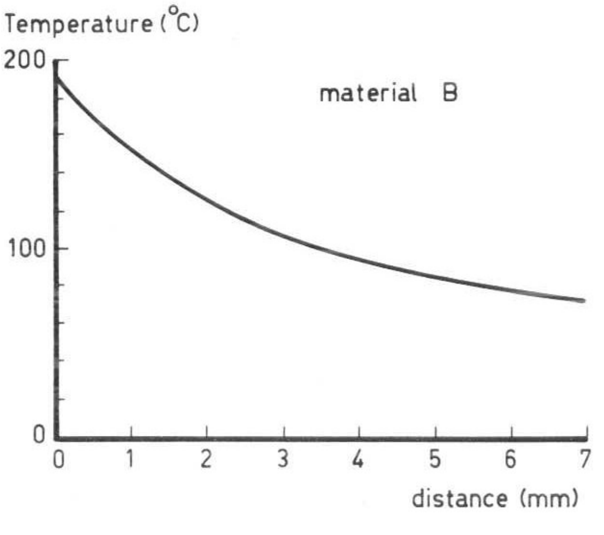

Figure 6 Temperature vs distance to the pipe end at the end of the heating period

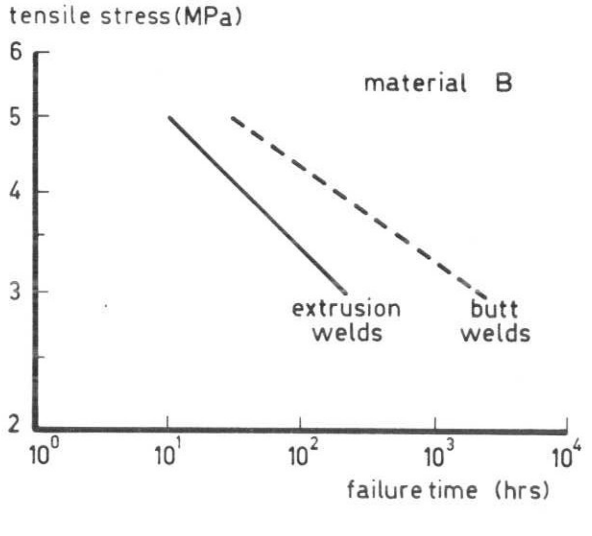

Figure 7 Static load test results (80°C, detergent) of welds (minimum failure lines)