A THEORETICAL APPROACH TO THE PRACTICAL PROBLEMS INVOLVED IN JOINTING DIFFERENT PE GRADES

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The compatibility of the various PE materials can be theoretically described by four different theories explained in this text. It is shown that the PE types investigated do not differ with respect to disperse and polar surface energies.

The applicability of the theories to socket, electro, and butt fusion and their limitations are described.

1. Introduction

Together with PVC,polyethylene (PE) is one of the oldest plastic materials used in large-scale pipe line production. While LDPE (low density polyehtylene) is used mainly for water service pipes,HDPE (high density polyethylene) is much more generally applied. The individual markets can be roughly subdivided as follows:

- water distribution (service pipes)
- irrigation
- industrial piping systems
- gas distribution

Especially in gas distribution applications,HDPE has replaced metal materials for gas distribution networks with up to 4 bar operating pressure. In the UK, about 80% of all mains and 90% of all services are made of HDPE /1/. The material was first applied in the 50's. Its development is exemplified by the figures of the US market.(Fig 1).

The success of this material for plastic pipelines is based on chemical resistance, noncorrosive behavior, simple installation, and fully developed welding techniques:

- socket fusion
- butt fusion
- electro fusion

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During the early stages of development, European manufacturers basically offered three materials with essentially the same physical properties. Advances in plastics engineering and sophistication of national standard specification during the 60's have led to the continuous improvement of existing materials, the development of new materials, and the appearance of new manufacturers. However, the development in Europe did not take the same course as in the USA. Differences are noted especially with regards to test requirements and test levels.

Fig. 2 shows a survey of some current materials with a comparison of their melt flow indices.

The unavoidable competition for market shares among individual raw material manufacturers has resulted in purely marketing-oriented designations and arguments for identical materials. Slow work progress in national standards as well as in international ISO commitees yet increased confusion among end users. For example, one specific material may be termed as HDPE, MDPE, type 1, type A, or PEM. An additional problem is created by the fact that plastics engineers have not yet agreed on universal acceptable limits resulting from internal pressure tests. Limits determined by standards may be exceeded by all materials; differences originate mainly from the extrusion process.

The resulting confusion among end users during the 70's has directed the focus on the question of compatibility of different materials. To be safe, some users only allowed welding between parts of identical material.

On the basis of comprehensive practical tests with the above-mentioned welding techniques, the German Welding Society issued a regulation which essentially stated that all PE types in the melt flow index range between 0.4 and 1,3 g / 10 min could be jointed to each other regardless of the welding technique (white area in Fig. 1). This regulation was internationally accepted in 1980 /3/.

Although this regulation is based on short- and long-term investigations, the theoretical confirmation of the results found in laboratory tests and verified in thousands of practical applications has not yet been comprehensively described.

2. Theoretical background

To describe the mutual adhesion of plastics, four theories have been basically applied (Fig.3). They will be briefly described and evaluated below.

2.1 Adhesion theory /4, 5, 6, 7/

Energy is required to isothermically increase the surface of a weld. The energy required for isothermal formation of 1 cm^2 of surface corresponds to the specific free surface energy, also termed surface tension. This surface energy can be subdivided into a disperse and a polar portion.

$$\sigma = \sigma^p + \sigma^d$$

The polar portion comprises all dipolar, induction, and hydrogen bridge bonds. The component σ^d comprises the nondirectional dispersion forces.

When two substances make contact, a contact surface energy is built up at the contact surface: $\sigma_{1,2}$
(Fig.4).

Maximum adhesion is obtained when the specific contact surface energy is zero, i.e. the materials are identical. The Owens-Wendt equation shown in Fig.4 shows that this is the case when the quotients

$$\frac{\sigma_1^p}{\sigma_2^p} \quad \text{and} \quad \frac{\sigma_1^d}{\sigma_2^d} \quad \text{are equal.}$$

Fig.5 shows a graphic representation of this relationship.

In the scope of a common test program with the Plastics Processing Institute (IKV) Aachen, the effective values of the various PE pipe grades were investigated. European and American materials were tested with three substances:

- distilled water
- formamide
- ASTM 39

The measured contact angles were evaluated according to the status equation by Owens and Wendt which in combination with Young's equation results in a straight line equation (Fig. 6).

If all materials investigated are represented in one diagram, it can be seen that the differences between materials are within the measuring tolerance(Fig7)

The individual results in Table 1 show that neither the melt flow index nor the coloring of the materials influence the values.

2.2 Viscoelastic contact theory /8, 9, 10/

The viscoelastic contact theory is based on the fact that the surfaces of the jointed parts are brought so close to each other that van der Waals forces, i.e. dipolar, induction, dispersion, or hydrogen bridge bondes, come into effect. According to the theory, this is due to the fact that the surfaces of the jointed parts, e.g. pipe and socket fusion fitting, are deformed by the welding pressure, and the boundary surface is formed as a function of time. This is illustrated by the model shown in Fig. 8.

As shown by GABLER /8/, this requires thermal induction periods of 10 minutes and more, which contradicts practical experience with the three mentioned welding techniques.

2.3 Diffusion theory /11, 12, 13/

The Diffusion theory was developed by VOYUTSKI and VASENIN and assumes that the molecules or chain segments diffuse into each other (Fig. 9). The diffusion theory is applicable if the following conditions are fulfilled:

a) the polymers must be mutually soluble,
b) the macromolecules must have sufficient mobility.

The description of solubility (also thermed in the physical chemistry literature compatibility) is very complex and demanding (13). From a thermodynamic point of view, free enthalpy determines whether mixing or separation takes place. For spontaneous processes, this is characterised by the condition $\Delta G \leq 0$. The influence of the mixing enthalphy ΔG is described by the interaction parameter which is basically determined by the physical structure. This structure being identical for all polyethylenes (additives in ppm magnitudes can be neglected), identical solubility parameters can be assumed, i.e. compatibility is assured.

The requirement of high mobility of the macromolecules makes it necessary to exceed a certain minimum temperature with all welding techniques since the diffusion range at room temperature would only be a few Angstroms. The measured boundary layer thicknesses are much greater because they are formed at higher temperatures.

Application of the calculation methods shows that the required own diffusion times are longer than the welding times used in practice.

2.4 Flow process theory

This theory was developed for the field of plastic pipes by POTENTE and DE ZEEUW /14, 15/. It assumes that during the jointing process, the welding pressure and the welding temperature create flow fields, i.e. flow movements. This is illustrated by the heating element butt fusion shown in Fig. 10
As a result, the thermal displacement processes are superposed by mechanical displacements which can become so intensive that mixing occurs in the jointing zone. Such processes are faster than diffusing or viscolelastic contact processes and, in the case of heating element butt fusion, have a serious impact on subsequent strength. For heating element butt fusion, a mathematical model was established to combine the process and material parameters with the obtainable joint quality.

2.5 Criteria

Assuming the validity of all these theories, a set of criteria can be established for the compatibility of the various PE types:

a) The ratio of polar and disperse surface tension portions should be balanced.

b) The viscoelastic properties, especially with regard to the processing temperature in jointing, should be in the same order of magnitude.

c) The solubility of the polymers, i.e. their chemical structure, should be the same.

d) For jointing processes, the parameters of temperature and pressure are of primary importance.

Practical experience shows, however, that these criteria may be necessary but not sufficient for all techniques.

3. Application to the various welding techniques

3.1 Butt fusion

The investigations by POTENTE et al. have shown that flow processes have a significant influence on joint quality.

Fig. 11 a) shows the example of an ideal seam geometry not very frequently found in practice. If polyethylenes with highly different melt flow indices are welded together, the geometry shown in Fig. 11 B may arise.

Especially when high tension or internal pressure is applied and stress crack generating fluids are used, early failures must be expected, caused mainly by notch effects.

For this technique, it is necessary that the melt flow indices of the pipes to be jointed do not differ too much from each other.

The values given by DVS-regulation 2207 /2, 3/ are useful in practice, i.e. the melt flow index should range between 0.4 and 1.3 g/10 min.

In theory, materials with greater difference in melt flow indices could also be jointed. This could be achieved by using different heating-up times, i.e. the increase of the heating-up period for the material with the lower melt flow index.

3.2 Socket fusion

This technique also creates a melting movement but not as extensive as in heating element butt fusion (Fig. 12).

It can be seen that the original contact surface is maintained in large parts of the jointing surface. It can thus be concluded that especially the adhesion theory and the viscoelastic contact theory are applicable to this jointing technique.

Here again, the melt flow indices should be in the same range as in heating element butt fusion. If not, the marked difference of seam geometries may cause a notch effect.

3.3 Electrofusion

The difference of this technique from the other two techniques mentioned lies in the fact that no significant melt flow occurs in the jointing zone (Fig. 13).

As a result, the obtainable joint quality can be described mainly by the adhesion theory, the diffusion theory and the viscoelastic contact theory. If we assume that the adhesion theory still provides the best possibilities for measuring, it can be concluded that the application range of electrofusion is much broader than that of the other techniques. I.e. it makes it possible to join materials with highly different melt flow indices.

Internal pressure tests and tensite tests have been carried out to verify the MFI range of 0.4 - 4.3 g/10 min.

4. Limitations

Adhesion forces only come into effect if very close contact can be established between the jointing surfaces of the pipe or pipe/fitting combination. If one of the mentioned criteria cannot be fulfilled, e.g. because chemical contamination has led to the formation of a surface layer (Fig. 14), adhesion will be poor and the fusion will fail early /16/.

As a result, the national codes of practice require mechanical cleaning of the surface to be jointed. /2, 17/

5. Conclusions

The practical experience that the various Polyethylenes used for pipes and fittings are compatible is confirmed by theoretical considerations. This applies especially to "European" raw materials.

Further research in this field is necessary and is carried out because of the growing importance of the PE pipe market. We suggest that the field of heating element butt fusion be more closely investigated since it is certainly the most important field with regard to the number of joints executed.

It should be further mentioned that the conclusions of this paper are strictly related to PE/PE joints. Attention is drawn to the fact that joints between PE and other materials (i.e. PP), - which do not generally occur in practical piping systems, require an additional criteria /8/. In these cases also the expansion coefficients of the two materials should be equal.

With regard to the national codes of practice, the problem of weldability of PE types no longer exists. The only unsolved problem is to agree on a universally applicable designation of PE types (as was the case until 1970 with the term HDPE as opposed to LDPE) in order to eliminate confusion among end users.

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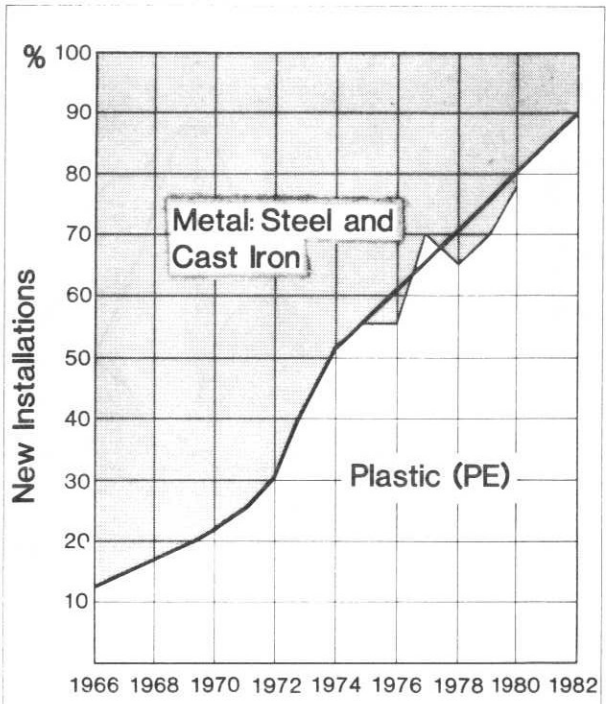
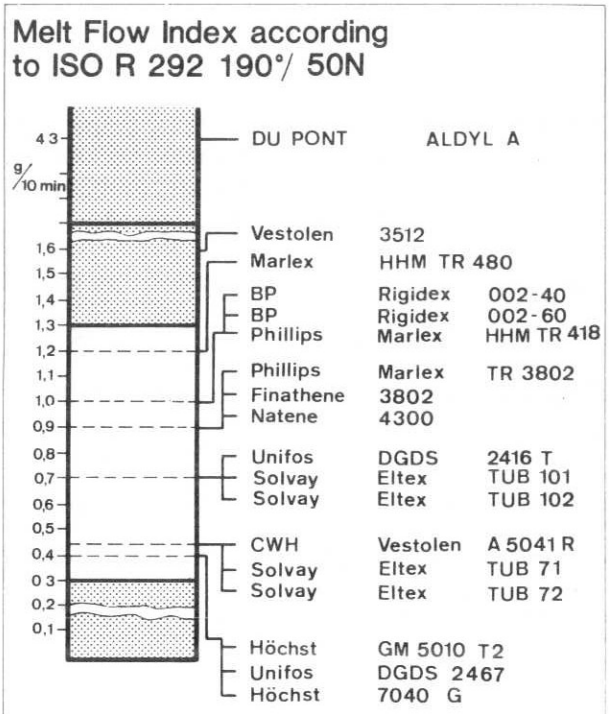


Development of PE Distribution-Systems in USA

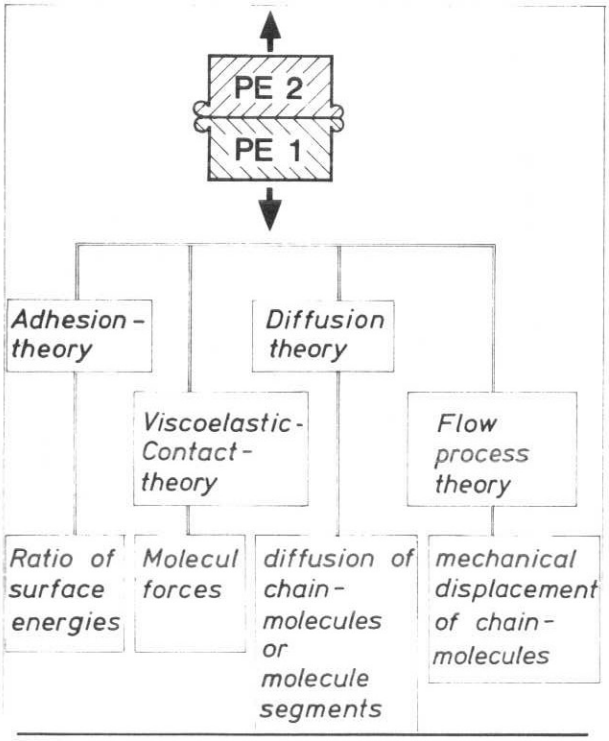
Source: P and G Journal

Fig.1



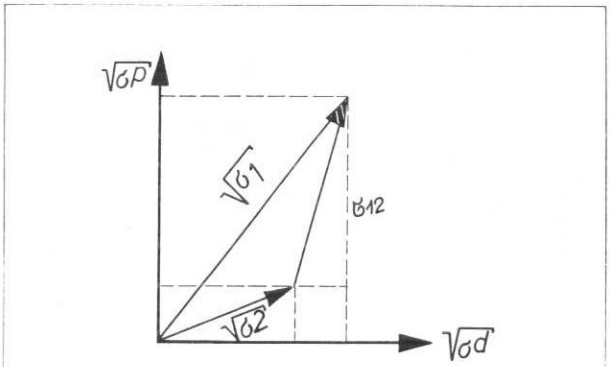
Melt Flow Index of Different PE-Grades

Fig.2



Different Theories with Respect to Jointing of Plastics

Fig.3



$$(\sqrt{\sigma_1^d} - \sqrt{\sigma_2^d})^2 + (\sqrt{\sigma_1^p} - \sqrt{\sigma_2^p})^2 = \sigma_{12}$$

$$\sigma = \sigma^d + \sigma^p$$

Owens-Wendt Equation:

$$\sigma_{12} = \sigma_1 + \sigma_2 - 2\sqrt{\sigma_1^p \cdot \sigma_2^p} - 2\sqrt{\sigma_1^d \cdot \sigma_2^d}$$

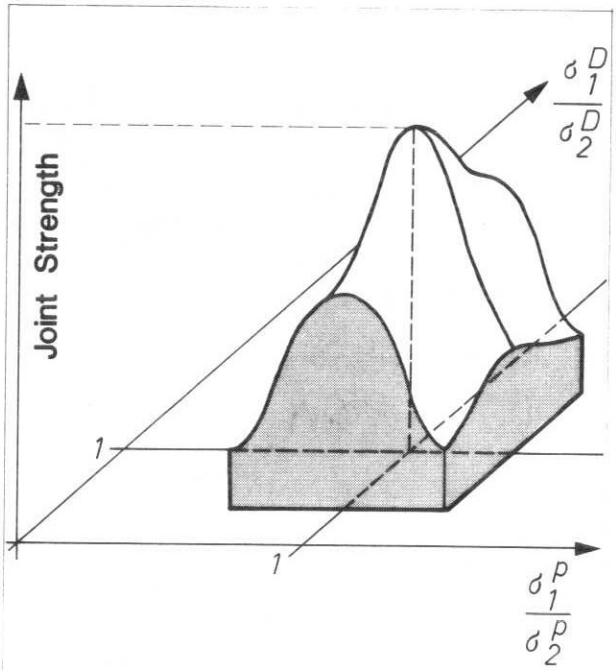
Definition of Contact Surface Energy

Fig.4

Table 1

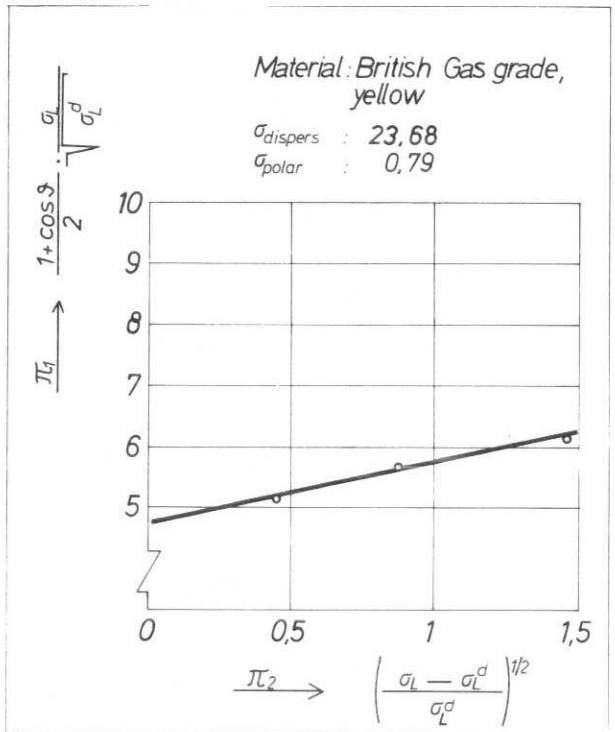
Material	Colour	Melt Flow Index 190/5	Polar Surface Energy $\frac{mN}{m}$	Dispersed Surface Energy $\frac{mN}{m}$
European	Black	0,4	0,99	23,19
European	Yellow	0,4	1,25	22,67
European	Black	0,7	1,11	22,29
European	Yellow	0,7	1,04	22,93
European	Yellow	1,0	0,79	23,68
American	Tan	4,3	1,86	21,54
American	Black	1,5	0,79	23,68

Results of Surface Energy Measurements



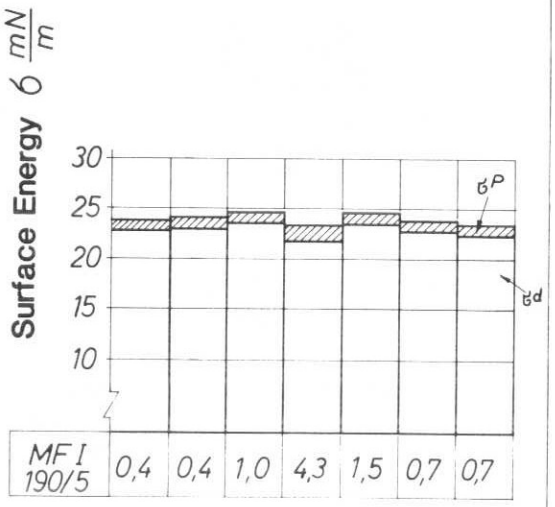
Graphical Representation of Surface Energy Criteria

Fig.5



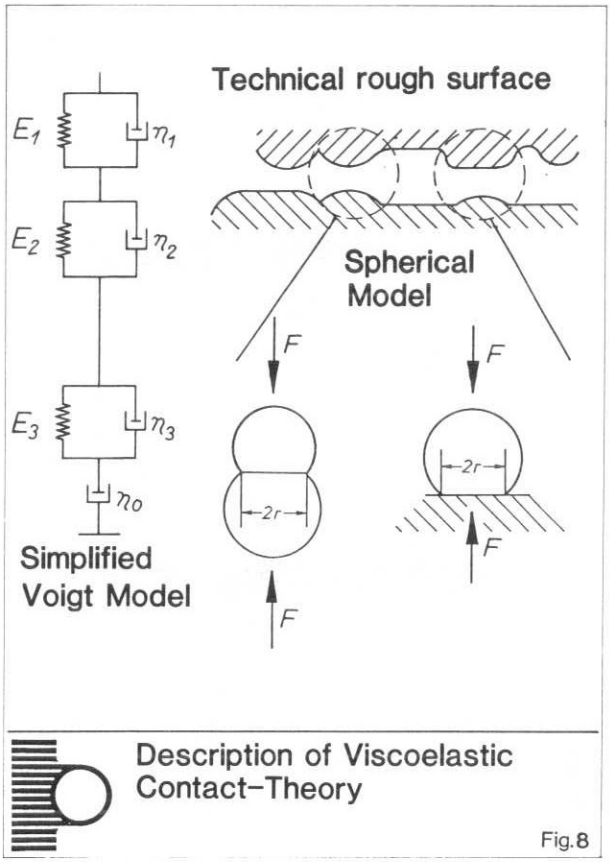
Determination of Surface Energy

Fig.6



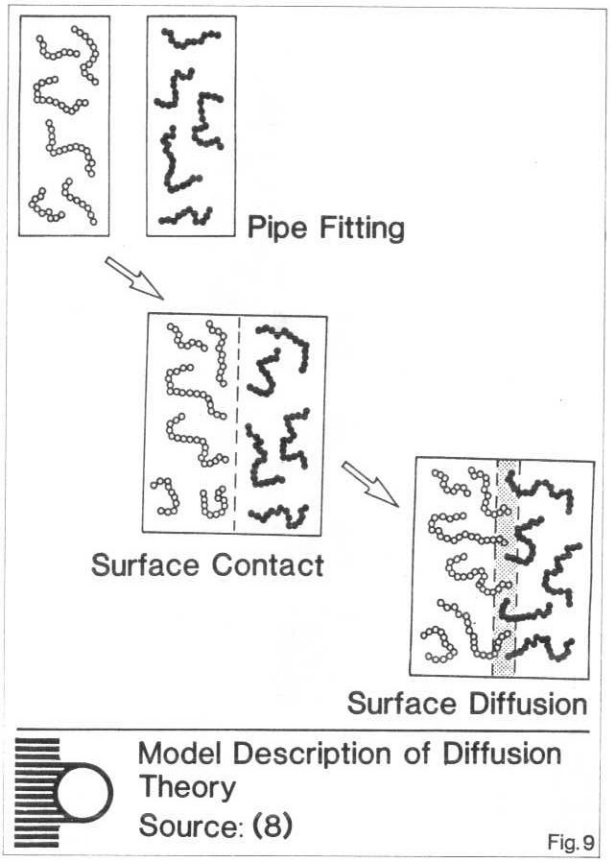
Surface Energy of Different PE Grades

Fig. 7



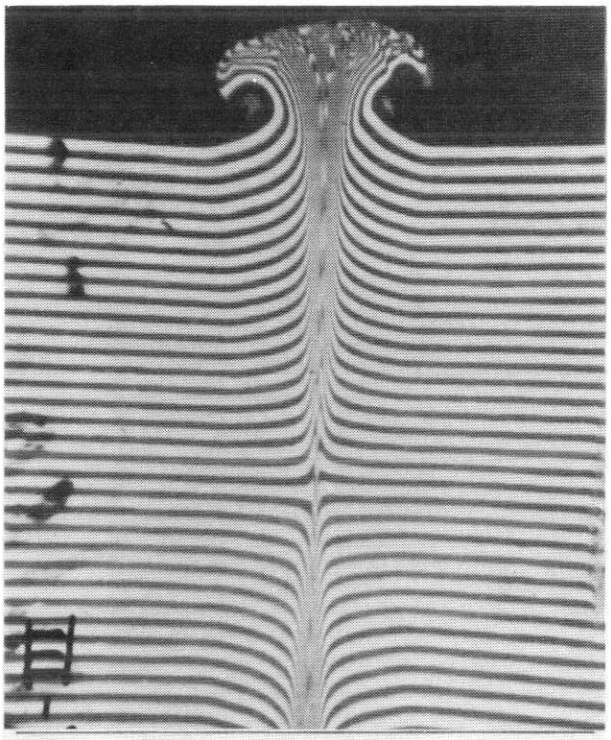
Description of Viscoelastic Contact-Theory

Fig.8



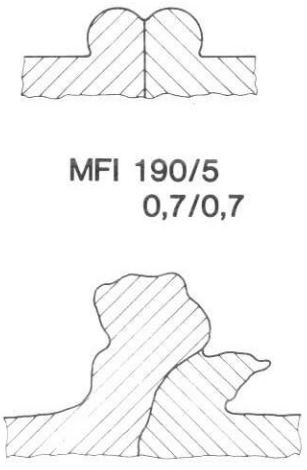
Model Description of Diffusion Theory
Source: (8)

Fig.9



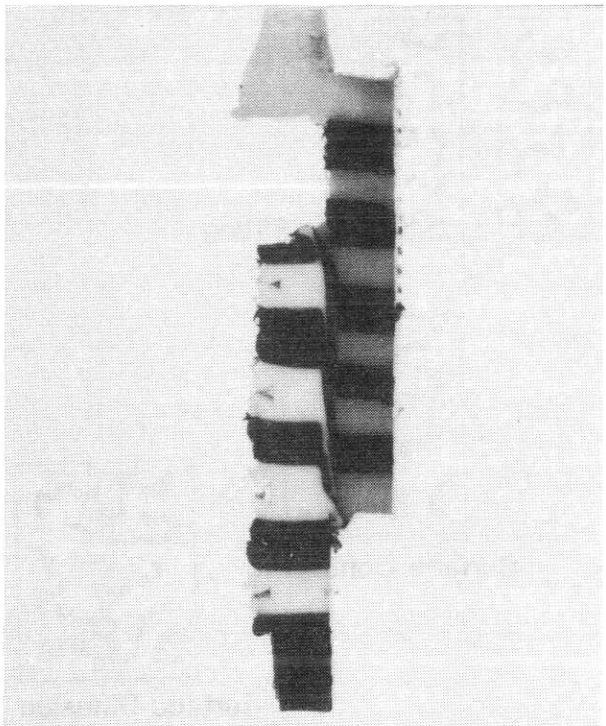
Butt fusion Sample
Source: Bielomatic

Fig.10



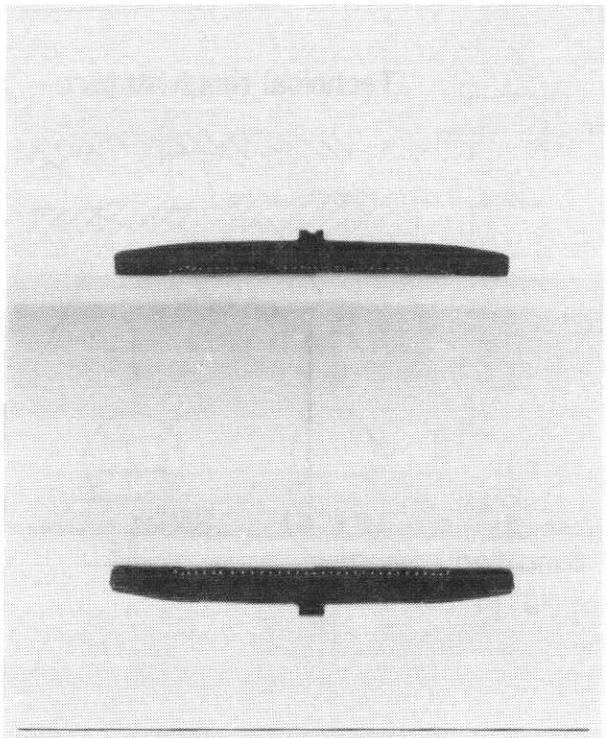
Butt fusion Joints

Fig.11



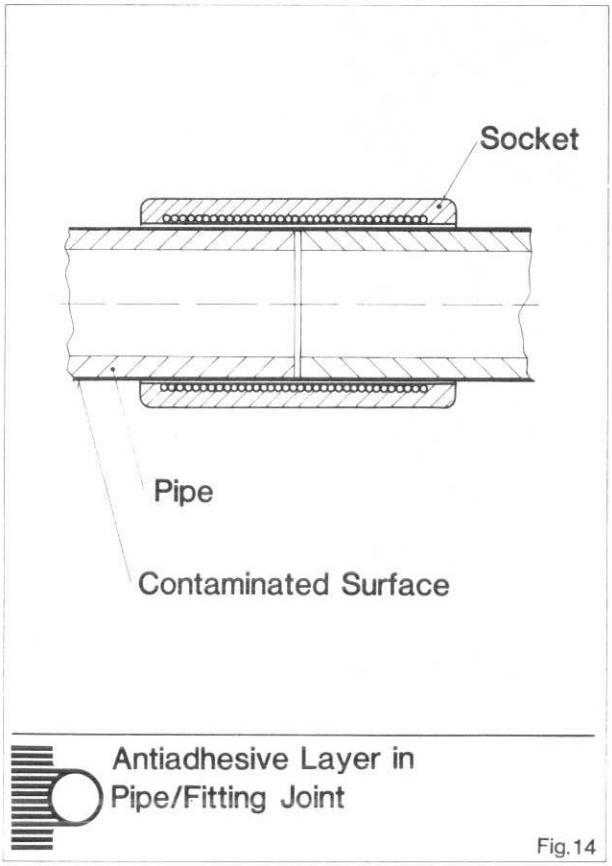
Socket Fusion Sample

Fig. 12



Electro-fusion Sample

Fig. 13



Antiadhesive Layer in Pipe/Fitting Joint

Fig. 14