Laser simulated imperfection (LSI) for remaining life assessment of the thermoplastic pipes

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1. General considerations regarding the remaining life of thermoplastic materials pipes

Elaboration of the new materials and/or properties improvement of the existing ones represents one of the major priority directions in the research field of thermoplastics and composite material.

On the other hand, before launching the new product on the market, it must be tested in order to asses the in-service using ability and to estimate the remaining life in safety conditions, for specific exploitation parameters.

Destructive Testing give us data regarding to the structure and the toughness characteristics of the virgin material, or estimations for different service periods, under specified conditions. With this data one can establish and guarantee the extreme parameters of exploitation (temperature, pressure, time), in safety conditions, e.g. one PE 80 pipe is guaranteed to function at 20˚C for 50 years at 16 bar; the same product is recommended [1] to be used for 5 years at 60˚C at the same pressure.

These characteristics are assessed for the base materials, for ideal exploitation conditions respectively. In service, one finds a different situation with deviations from the ideal reference condition. On the other hand, the thermal joining processes affect the local characteristics of the material, leading in some particular situations to the modification of the long term characteristics of the component.

Also, during the joining process, setting in service, or in service operation time, deviations from the technological procedure or failures may appear, that are considered unimportant but which can affect the remaining life of the components.

External factors e.g. temperature can change the material structure in the joining area. As it is shown in [2], if the crystallization temperature is varied, modifications of thickness average of the stacks of lamellae and respectively the diffusion degree of molecules with lower molecular weight appear. Development of elongated lamellas in spherulites of a polymer is determined by the lamellae fragmentation by screw dislocation and radial biased growth under the influence of concentration gradients of segregation species.

Also, in case of improper joining temperatures (e.g. above 200˚C for polyethylene), there was shown in [3] that the oxidation and chain-session effect attended by creation of dislocations, odour and increase of the carbonyl content.

The material imperfections may appear even during the syntheses stage of the polymer. Imperfect mixing [4] affects the polymer properties. Thus, depending on the reactivity ratio and monomer composition, the mixing process can affect the copolymer composition and chain sequence length.

In case of the pure polymers, the crystalline spherulitic growth rate increases as the shear rate increases [5]. This phenomenon has been assumed to the decrease of the activation diffusion energy. In case of polymers blends [6], the processing conditions (shear rate) provide the interface modifications between pure A and pure B polymer, the modifications of morphology evolution and the composition of the polymeric blend, respectively.

The simulating of imperfections in order to study their evolution under different loading conditions is a fracture mechanics method [7] for estimating the in-service ability of some components with imperfections. Using this method the reaming live for the component of the structures can be estimated. For in-service evaluation of polyolefin pipes, in presence of the imperfections, a method was established [8] for determining the resistance to slow crack growth of polyolefin pipes, expressed in terms of time to failure in a hydrostatic pressure test on a pipe with machined longitudinal notches in the outside surface.

Since this test has been designed only for base material assessment and it is applicable to pipes with wall thickness greater than 5mm, this paper proposes a new testing method, considering also the thermal effect on the polymer structure through the joining processes using thermal sources. Thus, considering the factors that influence the pipe and the thermoplastic pipe welded joints quality [2-6], [9-13], this paper proposes a new procedure for obtaining simulated imperfections using LASER technique (Laser Simulated Imperfection – LSI Method). The method can be applied for the evaluation of the original properties of thermoplastic pipes and also for remaining life evaluation of the pipes after a service time in specific conditions, based on the fact that hydrostatic pressure affects the long term characteristic of the material [9].

2. Working procedure

2.1. Experimental material

For the experimental program regarding imperfections simulation samples extracted from high density polyethylene pipes were used. The simulation of imperfections was performed on the pipe with standard nominal diameter. Thus, samples simulated imperfections from Ø 32 × 3 mm pipes were created. The pipes were sampled by mechanical cutting at length: Lmin=400 mm. Because the pipe samples had to be tested under internal hydrostatic pressure, in order to establish a minimal length of the sample, to the reference length of the simulated imperfection (Lc=50 mm), there was also taken into account the necessary length for the tightening devices. For a good tightening, the frontal surface of the pipes' end was machined by facing.

2.2. Realisation of the sample with imperfection using LSI (Laser Simulated Imperfections) method

In order to simulate the longitudinal imperfections on PE pipes the LASER processing technique was used. Though most of the polymers are transparent to the laser beam wavelength the colouring additives from the base material do act as an energy coupling and heat transfer thus making possible the laser processing.

Nevertheless, depending both on the base material, the additive type and its concentration, a correlation between the laser beam process parameters and the penetration depth is required.

Furthermore this correlation may depend on the laser type (laser beam wavelength) and on the working mode – continuous or pulsed.

However the method is easy to use, fast and highly reproducible while the simulated imperfections are similar to the ones that may appear in the butt welded joints.

2.3. Testing method

The study of material behaviour in the presence of simulated imperfections is performed based on internal pressure testing at constant temperature. Internal hydrostatic pressure test at constant temperature was carried out to determine the bursting period of the sample on the given test conditions (pressure, temperature and environment) and for identifying the fracture character and the bursting position.

2.4. Testing equipment

For simulating the imperfections in the base material a Nd:YAG laser Trumpf HL 124P LCU (Trumpf GmbH, Ditzingen, Germany) with a fibreglass connected cutting head was used (Figure 1).

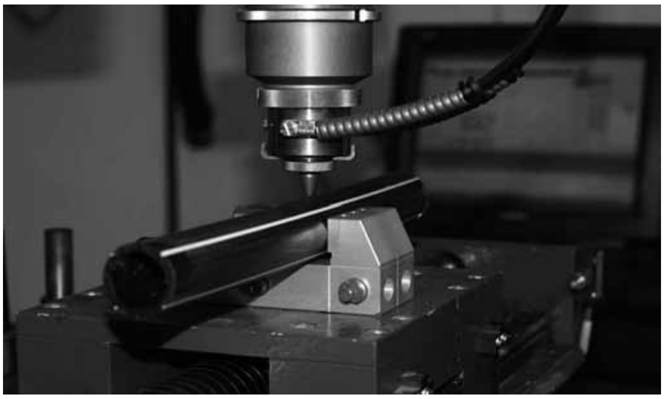

Figure 1. LSI experimental setup.

The characteristics of the laser are: maximum pulse peak power = 5kW, maximum average power = 120W, pulse duration = 0.3÷20ms, maximum repetition rate = 600Hz, and pulse energy = 0.1÷50J.

The inner pressure tests were carried out on computerized testing equipment which ensures an automated maintaining of the prescribed testing parameters (pressure and temperature).

This equipment (figure 2) allows the realization of the tests in two variants: "water in air" and "water in water", being composed of:

Figure 2. Pressure test equipment
a) Test Oven, b) Pressure test module, c) Test Bath.

• Devices that ensure tightness of the test samples and flexible connections to the pressure test module.

• A module that allowed to prescribe and control the test pressure, which ensures a maximal deviation of $^{+2}_{-1}$ % during the test.

• Constant temperature bath and test oven, which allows maintaining constant temperature with a maximal deviation of ± 1 °C.

3. Experimental results

In this section, an example of applying the LSI method for PE 80 polyethylene pipes is detailed.

For simulating the imperfections the laser process parameters were specific to pulsed laser beam cutting, e.g. short width rectangular pulse, relative high pulse peak power and high pulse repetition rate (55 Hz) in respect to the travelling speed (3.73 mm/s). As processing gas, Ar 99% at 6bar pressure was used. Preliminary experiments were performed to establish the process parameter adjustment space according to the desired penetration depths for the specimens (0.15÷1.5 mm). The data showed an appropriate linearity for penetration depending on the pulse peak power, so a programmed experiment was performed to establish the equation that correlates the penetration depth to the peak power pulse.

The data was graphically fitted (Figure 3) and the corresponding equation describing the penetration depth variation as a function to the pulse peak power for the targeted domain was established.

Using the mathematical equation was possible to calculate the pulse power peak necessary to simulate the required imperfections in the material. Furthermore, the calculated parameters were verified by doing a set of experiments and measuring the penetration depth. The measured data corresponded to the calculated one in respect to the experimental errors.

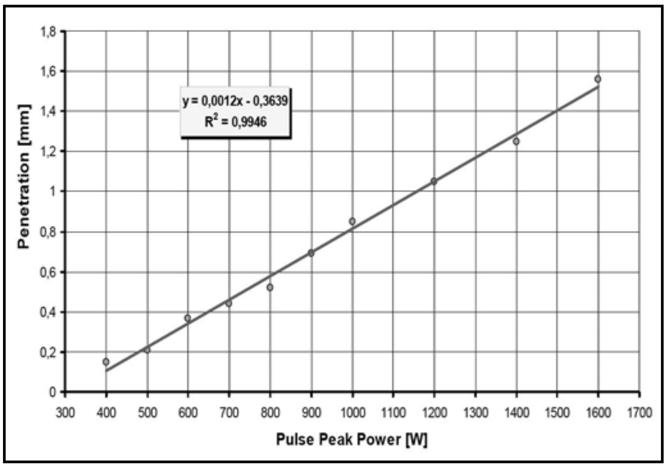

Figure 3. LSI calibration - fitted experimental data.

Using the established laser process parameters the necessary sets of specimens for the hydrostatic pressure tests were made.

The Figures 4 to 7 highlight through macroscopic and microscopic images few aspects of the notch profile and notch peak, before and after the internal hydrostatic pressure test.

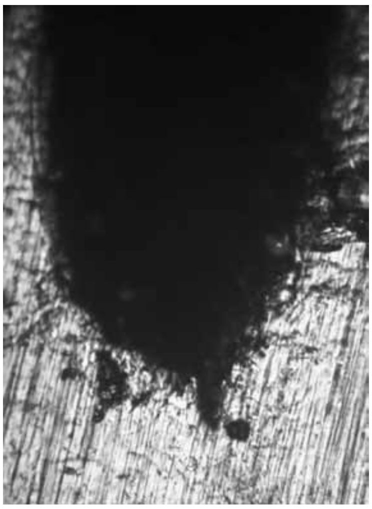

Figure 4. Notch profile simulated by LSI Method, before the internal hydrostatic pressure test.

For the LSI tested samples there were highlighted two types of fracture, which correspond to specific failure mechanisms: brittle fracture and ductile fracture.

Ductile fracture (Figure 5) occurred at high pressures after short period of load, the material near the crack being highly deformed, for imperfections with lower "A" characteristic dimension (figure 5a), or ejected to the outside, for imperfection with high "A" characteristic dimension (Figure 5b). The deformation by swelling of the pipe in the central zone is larger as the "A" characteristic dimension of the simulated flaw is smaller.

Brittle fracture (Figure 6) occurred at low pressures after a long period of testing and it is characterised by the appearance of transversal cracks towards the pipe's axis, developed from the basis of the pre-existing crack root. The failure mechanism is determinate by the "A" characteristic dimension of the simulated imperfection and the main testing parameters: pressure and temperature.

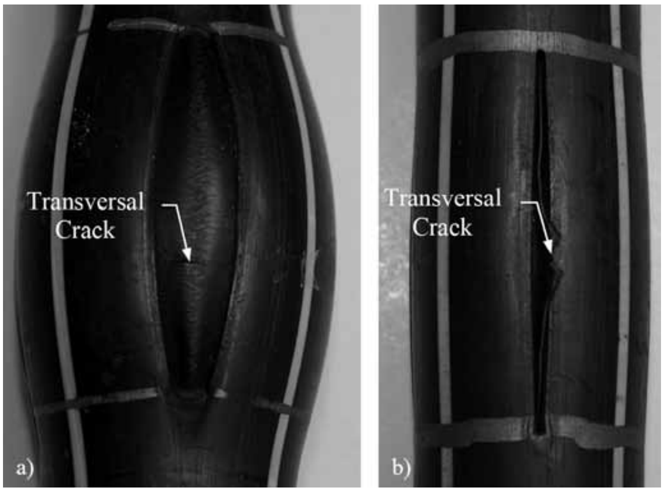

Figure 5. Ductile fracture – specimens with simulated imperfections by LSI Method:
a) Simulated imperfection, A = 5%, b) Simulated imperfection, A = 50% („A" represents the percent ratio between the notch depth and the thickness of the pipe wall).

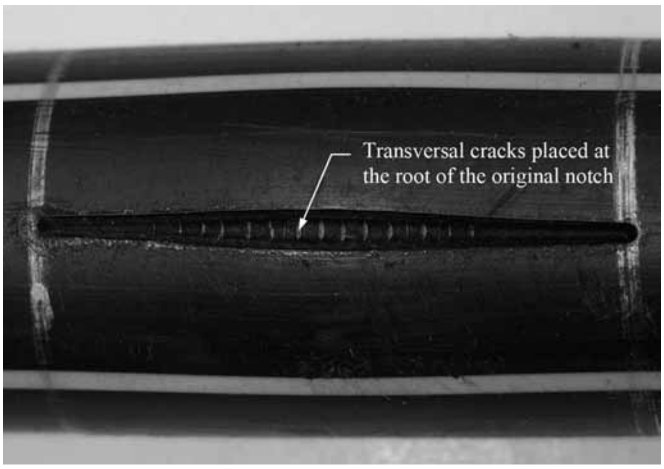

Figure 6. Brittle fracture - specimen with simulated imperfections by LSI Method.

The SEM micro-phractographic analysis of cracked zones, did highlight a fibrous texture of the material (Figure 7), with parallel fibres towards the pipe's axis. The symmetrically developed cracks towards the initial notches presented an elliptical shape with two peaks which are the local tension concentrators.

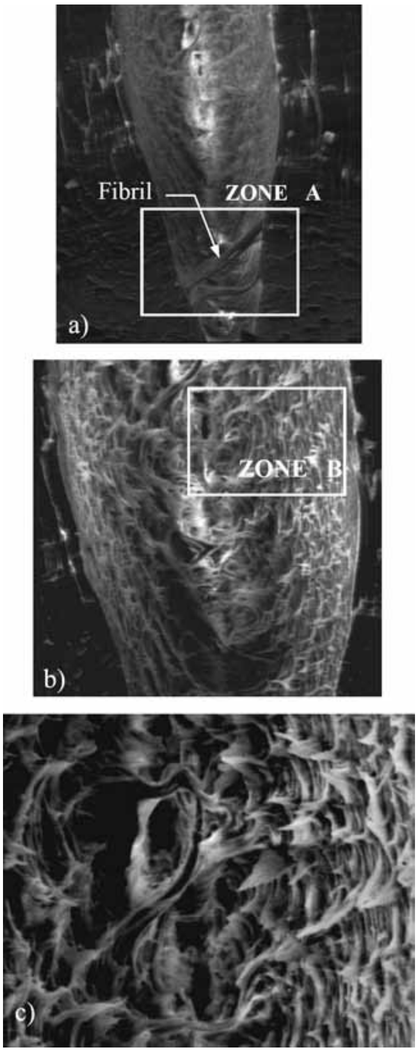

Figure 7. Micro-phractographic analysis by SEM technique:
a) 120X, b) 240X, c) 480 X – detail zone B [14].

Both plastic deformations of the fibrils (Zone A – initiation) placed in vicinity of the two crack peaks and fibrils ruptures (Zone B) were observed.

4. Conclusions

➢ Compared to the classical variant, the LSI method is not restrictive; it can be applied both in case of thick pipes and for thin pipes with thickness less than 5 mm or for capillary tubes.

➢ For simulating the imperfections, according to the test method for slow crack growth on notched pipes (notch test), the LSI method uses a concentrated laser beam, the notches may have dimensions up to 20 μm.

➢ Using LSI method for the determination of resistance to crack propagation, the material is verified / validated also for joining procedures which are using thermal sources. The behaviour in presence of the planar imperfections placed in critical zones with thermal affected material can be also analysed.

➢ The method can be applied for evaluation of the original properties of thermoplastic pipes and also for remaining life evaluation of the pipes after an exploitation period in given condition.

➢ The paper results may be used to study the in-time behaviour of typical planar imperfection of butt welded joints with heating element of thermoplastic pipes, under different loading conditions, in order to assess the critical imperfection which leads to the joints failure.

➢ Paper presents an application example of LSI Method for thermoplastic material of PE 80 type. The method may be also applied to other thermoplastics and / or advanced materials (e.g. composites), provided they are not transparent to the laser radiation, or containing the elements which favour the coupling with the laser beam.

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