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Fractographic study of high-density polyethylene gas pipe following Small Scale Steady State test

A. Pusz, K. Michalik*
Division of Metal and Polymer Materials Processing
Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: katarzyna.michalik@polsl.pl

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Materials

ABSTRACT

Purpose: The present work attempts to examine the failure performance of high density polyethylene [HDPE] gas pipe through a fractographic study of the fracture morphology following Small Scale Steady State test (S4). Failure mechanisms are discussed based on the fracture morphologies resulting from these tests. There are many instances where the rapid propagation of cracks is the result of fluid pressure acting on piping structures. This problem is recognized as one of the most important issues of dynamic fracture mechanics. A fractographic study of the HDPE type of a gas pipe has been undertaken.
Design/methodology/approach: Scanning electron microscopic (SEM) observations were used to identify elementary process involved in the crack initiation and propagation.
Findings: Based on an investigation of the Small Scale Steady State (S4) test, in order to assess the fracture behaviour of polyethylene (PE) gas distribution pipe material during rapid crack propagation (RCP). Failure mechanisms are discussed based on the fracture morphologies resulting from these tests. The influence of molecular architecture on the rapid crack propagation (RCP) resistance of high-density polyethylene pipes was investigated. It was concluded that high molecular weight, high crystallinity and a relatively narrow molecular weight distribution are important architectural attributes for RCP resistance.
Research limitations/implications: Applying S4 test is limited to thermoplastic materials.
Practical implications: Presented method can be applied for other thermoplastic materials in the future.
Originality/value: The expressed method can be applied in the future for developing the research on the process with rapid crack propagation of polymers.
Keywords: Engineering polymers; Fracture mechanics; S4 test; Rapid Crack Propagation; Pipe

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1. Introduction

Polyethylene (PE) is the primary material used for gas pipe applications. Because of its flexibility, ease of joining and long-term durability, along with lower installed cost and lack of corrosion, gas companies want to install PE pipe instead of steel pipe in larger diameters and higher pressures. In a result, rapid crack propagation (RCP) is becoming a more important property of PE materials.

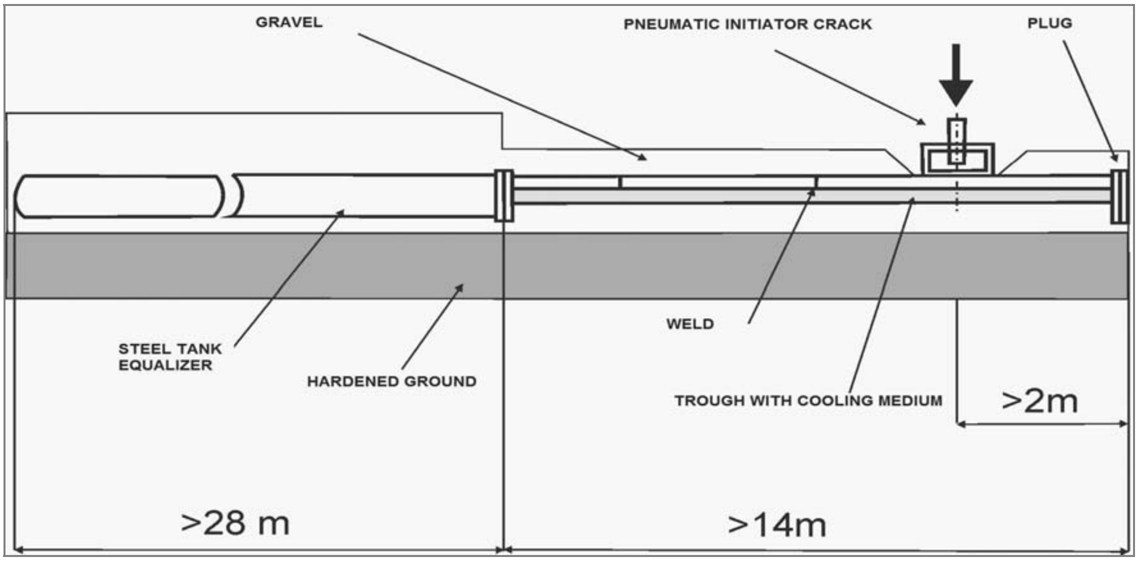

Fig. 1. Schematic view of the Full Scale Test configuration [11]

The key requirement in any fracture assessment of RCP is to determine the dynamic fracture toughness for the pipe material. This is frequently difficult to measure [1- 8].

When a pressurized PE pipe is subjected to a high velocity impact, a pre-existing or consequently initiated crack or flaw can propagate axially for many diameters at speeds in excess of 100 m/s. This event is referred to as rapid crack propagation (RCP) [9-15]. While RCP failures in PE pipes have been very rare, their potential consequences are very significant. Because of the catastrophic nature of RCP and its potentially dire consequences, pipe producers have to design pipes and applications so that RCP may be avoided under the worst possible conditions. This has led to the development of several tests, of which the full-scale (FS) and small-scale steady state (S4) tests are most relevant [16-21].

The FS test is designed to reproduce some idealized service conditions for a pipe being in service. It defines the absolute standard for RCP testing and delivers the final judgment on the pressure carrying capacity of a pipe. The S4 test attempts to simulate the same conditions within the confines of a laboratory are preferred for materials development and research because it offers significantly shorter test times and lower costs.

1.1. Full scale test (FS)

The test uses a pipe specimen of at least 14 m in length, which is placed in a trough with cooling water circulating around it to maintain the test temperature close to 0°C. The pipe is buried in gravel, of size 20–40 mm, to at least 100 mm above its upper surface. This both simulates recommended installation conditions and helps to prevent the pipe from floating during preconditioning in the cooling water. The pipe is extended by a steel pipe, of at least the same diameter and twice its length, in order to simulate an infinitely long pipe by attenuating decompression wave reflections from the specimen end. For the safety reasons, the pipe is pressurized with air or nitrogen rather than natural gas. A crack is initiated by a steel blade, driven rapidly into the pipe wall near one end, which is cooled to −60°C. RCP is said to have occurred when the crack extends axially to more than 90% of the pipe specimen length; otherwise, steady-state crack growth is believed to have been arrested [11]. Its essential features are shown in Fig. 1. The FS test details and procedures are listed in the ISO 13478 standard [22].

1.2. The small-scale steady state test (S4)

Since the full-scale test for the PE gas pipe, due to its size, is not easy in routine testing or quality control, people recently turned to the design the laboratory tests using short (5~7 diameters) specimens. The Small-Scale Steady State (S4) test has been developed by Leevers and his co-workers (Yayla and Leevers, 1989) in order to assess the fracture behaviour of PE gas distribution pipe material during rapid axial crack propagation.

In the S4 test, initiation results from impact of a chisel projectile with the pipe and the resulting crack propagates rapidly along the axial direction (see Fig. 2). Decompression, resulting from backflow of the gas, is restricted by a series of internal baffles which divide the pipe interior into a set of short chambers. These baffles prevent the axial decompression wave travelling ahead of the crack tip. Thus the crack tip pressure remains at the original line pressure for the S4 test. The advantage of this arrangement is that the steady state crack propagation condition can be achieved in a much shorter distance than in a full scale test [10,11, 14 -17].

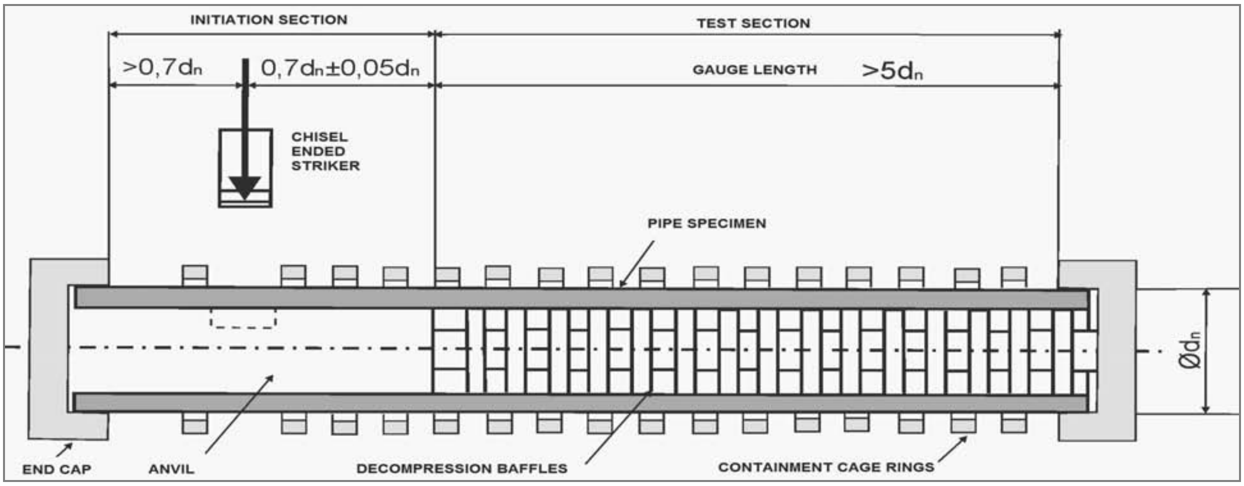

Fig. 2. Schematic view of the Small Scale Steady State (S4) test configuration [11]

Pipe wall flaring behind the running crack tip is restricted by an external containment cage, consisting of a series of rings having a small clearance of 5 mm to 15 mm from the outside surface of the pipe. A typical pipe diameter is 250 mm. The cage limits the extent of the pipe deformation, helping to maintain internal pressure by reducing the rate of radial gas escape. Thus it plays an important role in the S4 test and has a significant effect on the crack driving force in the pipe. The cage does not simulate the constraint on crack opening imposed by backfill in a buried pipeline because it does not reproduce the inertia, friction, or constitutive behaviour of soil or gravel. The S4 test details and procedures are listed in the ISO 13477 standard [23].

2. Experimental setup

Examining the resistance for rapid crack propagations was conducted at the Oil and Gas Institute in Cracow (See Fig. 3).

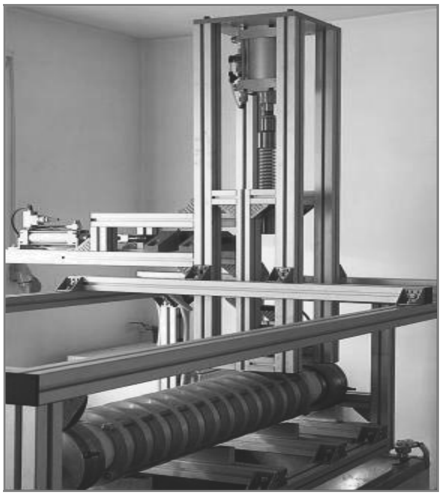

Fig. 3. Position to the Small Scale Steady State (S4) test in Oil and Gas Institute in Cracow

HDPE pipe with an external diameter of 160 mm and Standard dimension ratio (SDR) 11 were used to Small Scale Steady test (S4). The preparation of the test specimens was made according to the norm PN-EN ISO 13477:2008 (See Fig. 4).

The fractured surfaces were analysed macroscopically by using a scanning electron microscope (Zeiss SUPRA 35). Photographs were also taken with Olympus SP- 550 UZ camera. In order to show changes of the structure, the red dye was used.

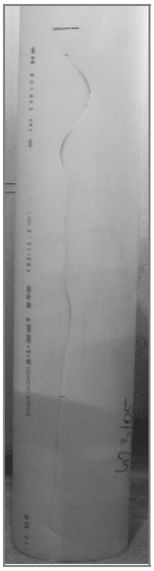

Fig. 4. HD PE pipe after the Small Scale Steady State (S4) test was investigated

3. Results

The fragment was divided into ten parts in order to separate fragments in which the crack had different character and the course (See Fig. 5).

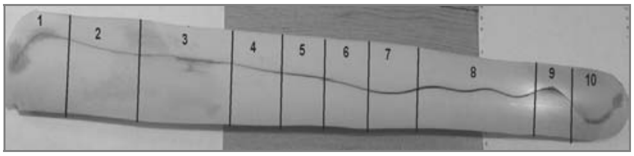

Fig. 5. Divided fragment of the sample

The propagation of the crack took place at different speed. In the picture the apparent damage is longer on the inside partition wall than on outside. The difference of appearing stresses on two sides of the pipe wall is a reason of such a crack (See Fig. 6.).

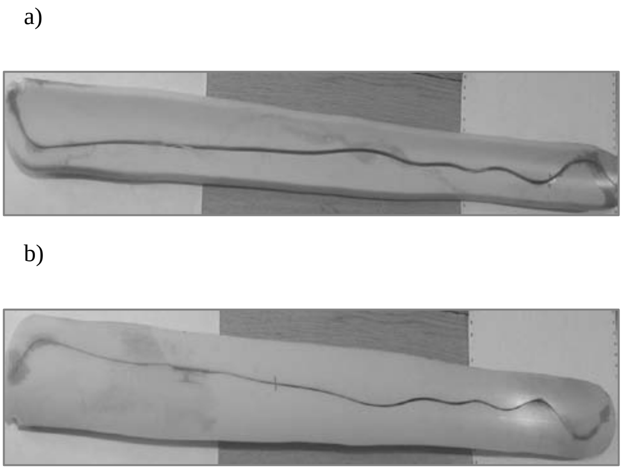

Fig. 6. Deformed fragment of the pipe: a) internal side of the wall of the tubular wire, b) the outside of the wall of the tubular wire

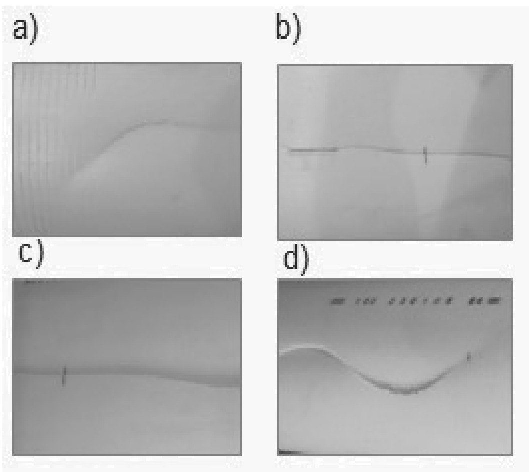

Fig. 7. Fragments of the sample depicting the course of the crack: a) beginning of the sample (closer side of the blade initiating the crack), b) fragment of it being struck by a blade, c) median part of the sample, d) end of the sample

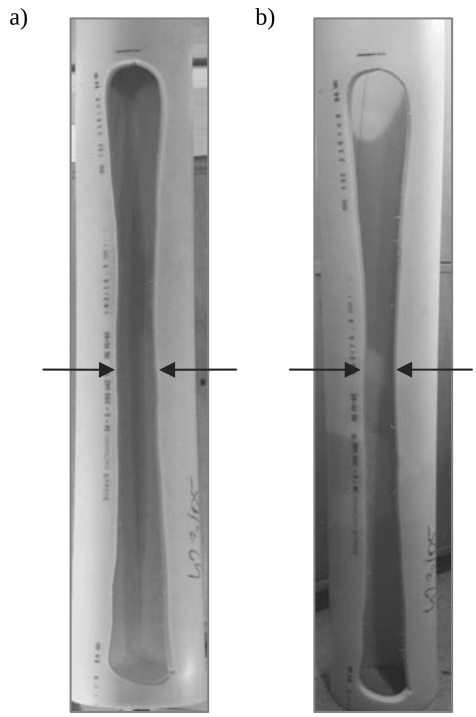

Fig. 8 . Deformed sample after the fragment has been cut; a) after 1 hour, b) after 2 weeks

The examination showed different character of cracking on different stretches of the sample. In the initial as well as in the final part of the pipe a fracture is appearing in the shape of the sine curve. However, in the central part damage has the shape resembling the beeline (Fig.7.a, b, c, d).

Inner stresses of material were a cause of the sample deformation (See Fig.8 a, b.).

Samples were dusted with gold. In the figure 9 short pieces of photographs were described, taken by a digital camera and a scanning electron microscope. Figures No. 10 to 13 are showing the structure which was observed.

The surface of tested samples was characterized by a structure of stretched fibrils arranged in parallel to them. Also, it was possible to observe the cellular structure.

The fibres are in fact highly drawn and oriented towards the crack propagation direction as it was suggested above. The ends of the fibres are pulled down from the material matrix. This highly deformed area is reported to be caused by the accelerated crack propagation before the final catastrophic rupture of the material (See Fig.10., Fig.11.).

Figure 12 is showing the fragment of sample 3 and the place of it having been impacted by a knife.

Sheets of fibres can be seen that were compounded upon each other (See Fig.13.). The crack propagation direction goes from the top to the bottom.

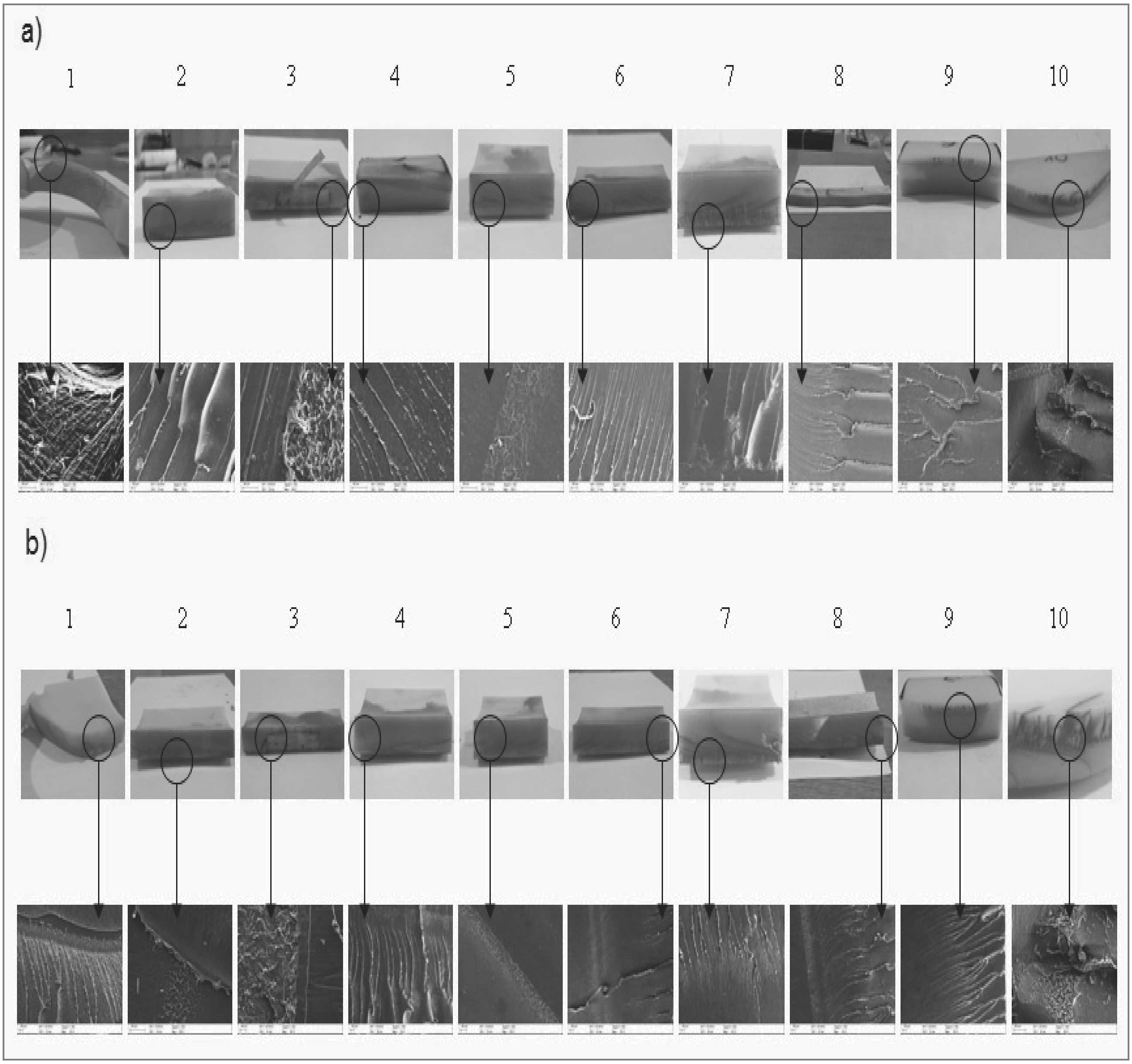

Fig. 9. Miniatures of photographs from the microscope and a camera: a) upper part of the sample, b) bottom part of the sample

4. Conclusions

Since gas companies use PE pipe in more demanding applications, such as: larger pipe diameters and higher operating pressures, the resistance of the PE pipe to rapid crack propagation (RCP) becomes more important. In this article we have discussed the phenomenon of RCP and two primary test methods used to determine RCP resistance the S4 test and the Full Scale test.

Experience showed different structures of surfaces arising as a result of cracking on individual fragments of the sample. On fragments of samples 1 and 10 which are the ends of cracks characteristic whitening appeared. Longer crack of the interior partition wall going towards the exterior one shows that during the S4 test greater stresses appeared in the centre of the tubular wire.

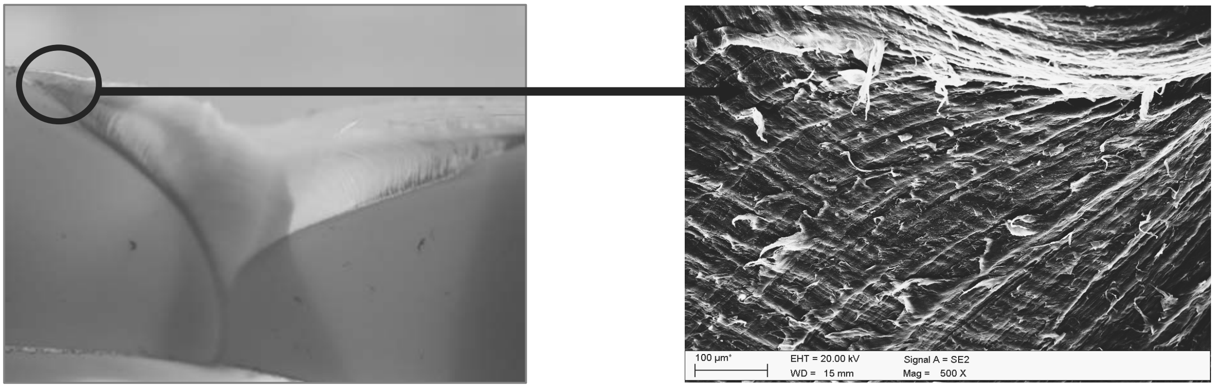

Fig. 10. Fragment of the sample No. 1 magnification 500x

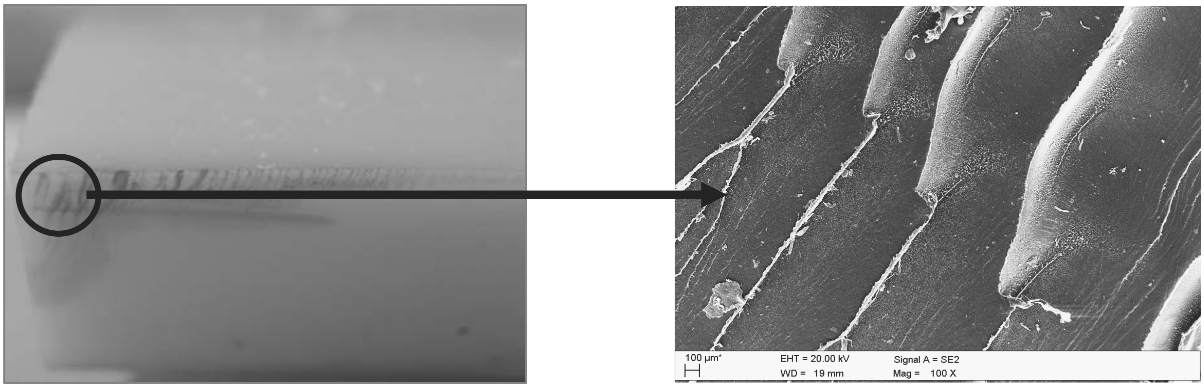

Fig. 11. Fragment of the sample No. 2 magnification 100x

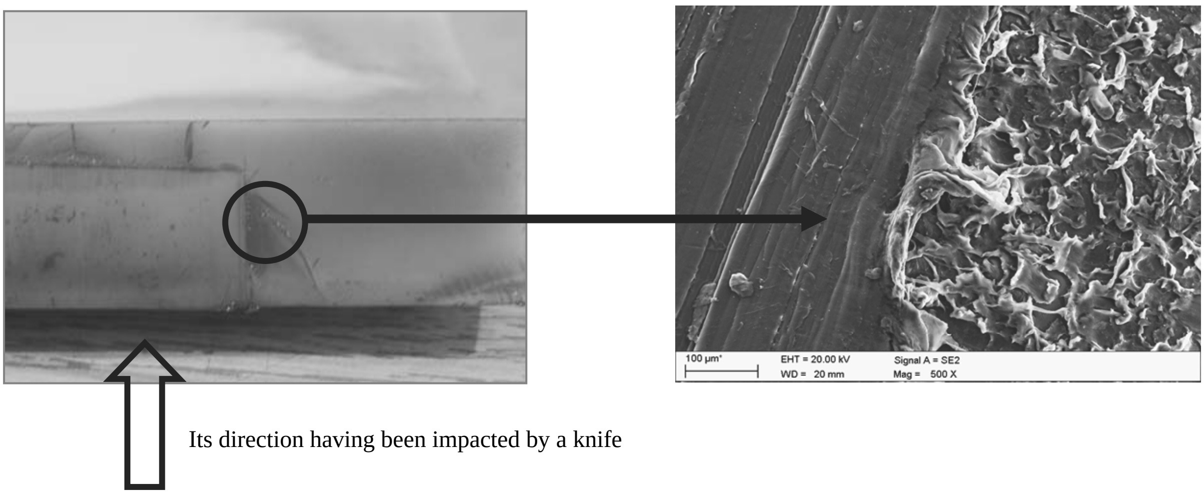

Fig. 12. Fragment of the sample No. 3 magnification 500x

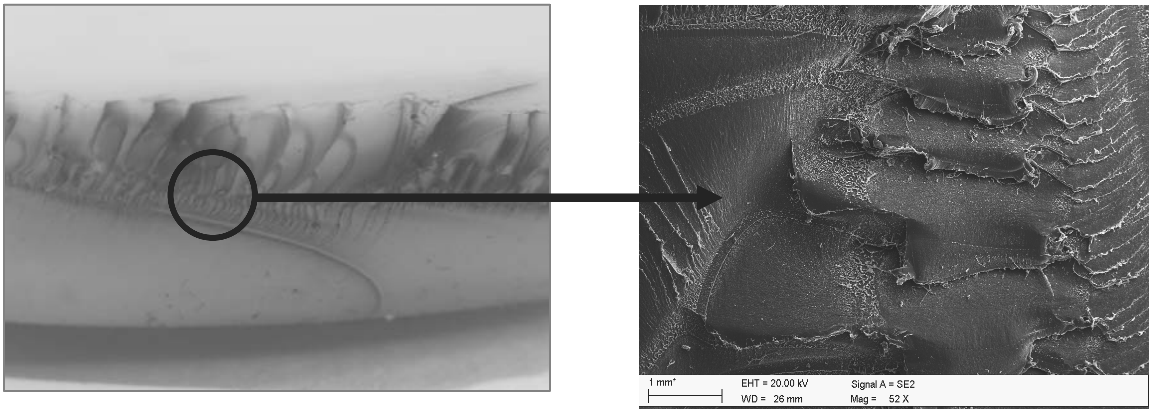

Fig. 13. Fragment of the sample No. 10 magnification 52x

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