Investigation of the Liquid Flow on Rough Surfaces to Solve the Problems of Liquid Penetrant Testing

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Abstract Cleanliness of the test surface is of particular importance in liquid penetrant testing. The surface cleanliness implies both the quality of surface cleaning from polluting substances, for example, oil, and the quality of its treatment, i.e. surface roughness. The surface roughness parameter increased to more than $Rz = 20\ \mu m$ can lead to unreliable test results since each groove on a rough surface will be a capillary for liquid spreading. Therefore, it will be difficult to completely remove the penetrant from the surface of the test object while removing its excess, which causes an indicator background of the surface and complicates defect detection. The study aims to determine the effect of liquid wettability on liquid penetrant testing results depending on the surface roughness. The paper proposes a mathematical model of liquid spreading on the rough surface depending on physicochemical properties of the liquid itself and material properties of the test object. The numerical modelling of the process is performed. The modelling results are confirmed experimentally, and statistical processing of the experimental results is performed.

1 Introduction

Liquid penetrant testing is currently one of the most effective methods of non-destructive testing to accurately identify defects on the surface of the investigated object, their length and direction. This method enables detection of defects with an opening of less than $1\ \mu m$ in products made from different non-porous materials, such as plastic, glass, and magnetic and non-magnetic metals [1–3].

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The main advantages of the method are:

- independence of test effectiveness on the product shape and geometry;
- ease of work performed;
- lack of need in complex and expensive equipment;
- method mobility;
- ability to detect defects on thin-walled parts with a thickness of 0.1–50 μm.

The method implies penetration of special liquids, flaw detection materials, into surface and through defects, which increase the light and color contrast of the defective area relative to the defect-free area during testing [4–8].

The quality of the flaw detection materials used depends on many parameters:

- properties of the materials included in the kit;
- technology used and testing conditions;
- ability of the kit to provide the required test sensitivity;
- surface state and the type of material of the test object [9];
- flaw detection kits include penetrant, cleaner and developer.

To ensure reliable detection of defects on the surface, penetrants used in testing should show good penetrating and wetting abilities [10, 11].

The penetration of liquids can depend on viscosity, density and polarity of the liquid, leakage and filtration properties, and roughness of the test surface [12, 13].

The surface roughness is considered as a combination of surface irregularities with relatively small steps within the base length.

On the one hand, the greater the roughness, the more distinctly its properties manifest themselves, which determines attraction or repulsion of the liquid from the surface. This effect can be attributed to the fact that at an edge angle less than 90° (for a smooth surface), the liquid penetrates into the cavities on the surface, similar to how it is absorbed into capillaries. This effect improves wetting of the test surface with liquid. If the contact angle is greater than 90°, liquid does not penetrate into cavities, which impairs wetting of the rough surface [14].

On the other hand, increased roughness improves liquid spreading, because each groove on the rough surface is a microchannel for liquid to spread. Therefore, some oils and fatty acids do not spread on a polished surface, but spread on the rough surface. Crack walls exhibit higher roughness parameters than the surface treated. Therefore, it should be expected that in clean crack cavities, liquids will show higher degree of wetting, and hence higher penetration [15, 16].

If the surface roughness is greater than the parameter $Rz = 20\,\mu$m, excess penetrant cannot be completely removed due to micro-grooves on the surface, which causes formation of a false indicator background and, hence, leads to unreliable testing results [17–20].

The study aims to determine the effect of wettability, namely, liquid spreading on the rough surface, on liquid penetrant testing results. The proposed program code increases the quality of studies aimed to determine the liquid flow in capillaries for research purposes, and it can be used to develop new flaw detection materials.

2 Program Description

A Wettability program was developed to reveal the effect of surface roughness on liquid spreading.

The program is based on the equation of liquid spreading on the rough surface, according to the so-called hydrodynamic viscous mode [2], in which the radius of the spreading spot is calculated using Eq. (1).

$$r = \sqrt[\frac{1}{4}]{\frac{4 \times \cos \Theta \times m}{\chi \times \pi \times \rho \times \eta \times K \times \sigma} \times t} \tag{1}$$

where r is the spot radius at time t (measured in m); θ is the contact angle of wetting (measured in degrees); K is surface roughness factor (dimensionless quantity); m is liquid droplet mass (measured in g); χ is the coefficient approximately equal to 10, which takes into account the increase in friction forces in the liquid due to the presence of the angular velocity of its flow (since each elementary trickle expands simultaneously when moving along the radius); ρ is liquid density (measured in g/cm^3); η is liquid viscosity (measured in Pa $\times$ s); σ is surface tension coefficient (measured in N/m).

The surface roughness factor was determined as the reciprocal of the arithmetic mean height of roughness Ra (2):

$$K = \frac{1}{R_a} \tag{2}$$

Figure 1 shows a block diagram of the developed program.

If the equation parameters are incorrectly set, the program displays an error message and asks to re-enter the data correctly.

The interface of the program for computer simulation of the effect of liquid spreading on the rough surface is shown in Fig. 2.

The left side contains the input and output windows of the task parameters. These windows are related to geometric and material parameters of the model and to parameters of the calculation method and graphical interpretation of the results. The first block contains the following parameters:

- mass of a liquid droplet (measured in g);
- liquid density (measured in g/cm^3);
- liquid viscosity (measured in Pa $\times$ s);
- wetting angle (measured in degrees);
- roughness factor (dimensionless quantity);
- time of observation (measured in s);
- surface tension coefficient (measured in N/m);
- the number of points is the parameter required to plot a common graph of modelling results with varied task parameters.

Fig. 1 Block diagram of the
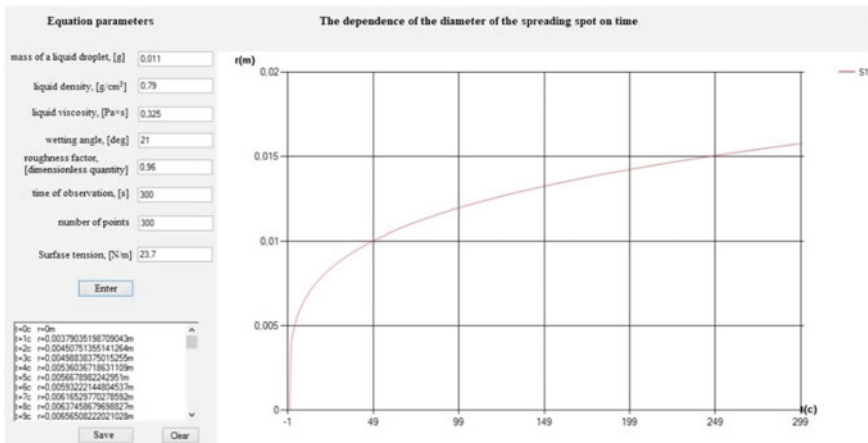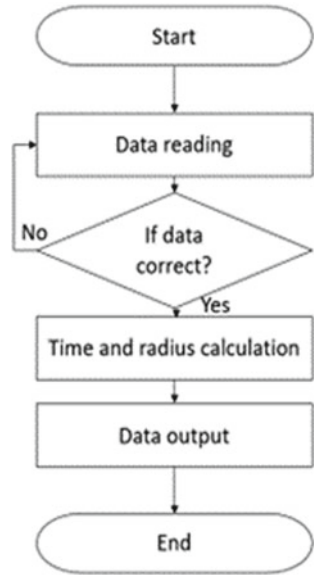wettability program

Fig. 2 Interface of the wettability program

An output field for intermediate results is in the lower left corner. The field is a simplified text editor that enables viewing of all intermediate values and operating them if necessary. The editor includes two columns—the current time value and radius of the spreading spot.

We have studied spreading of an acetone-based penetrant on plastic surface with various roughness areas. The roughness parameters Rz were 10, 20, and 30 μm.

Table 1 Values of the main equation parameters

Liquid	Droplet mass [g]	Liquid density [g/cm^3]	Liquid viscosity [Pa × s]	Wetting angle [deg]	Surface tension [H/m]
Acetone	0.011	0.79	0.325	21	23.7

Table 1 shows the values of the main equation parameters for acetone liquid and plastic material.

We have studied spreading of an acetone-based penetrant on plastic surface with various roughness areas. The roughness parameters Rz were 10, 20, and 30 μm.

These equation parameters were entered into the input windows of the Wettability program, and modeling of liquid spreading on the surface was performed with different roughness parameters.

3 Model Experiments

Table 2 presents the modeling results of the acetone-based penetrant spreading on a plastic plate with regard to various roughness parameters.

Graphical interpretation of the results is presented in Fig. 3.

The obtained curves indicate that the surface roughness affects the process of liquid spreading. The increased surface roughness leads to the increased size of the spreading spot; therefore, liquid spreads better on the rough surface.

Table 2 Modeling results of dependence of liquid spreading on time

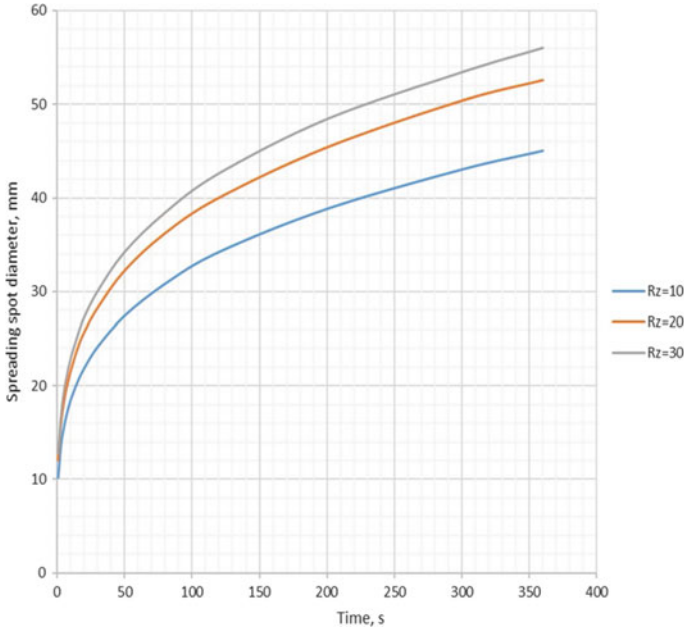| D [mm] t [s]	Rz = 10 [μm]	Rz = 20 [μm]	Rz = 30 [μm]
1	10.2	12.0	12.8
3	13.6	15.8	16.8
5	15.4	18.0	19.2
7	16.8	19.6	20.8
10	18.4	21.4	22.8
15	20.3	23.8	25.2
20	21.8	25.6	27.2
30	24.1	28.2	30.0
50	27.4	32.2	34.2
80	30.8	36.2	38.4
120	34.2	40.0	42.6
200	38.8	45.4	48.4
300	43.0	50.4	53.4
360	45.0	52.6	56.0

Fig. 3 Modeling results of liquid spreading on the rough surface

4 Experimental Study of Liquid Wettability

The following experiment was conducted to test the Wettability program.

Acetone-based penetrant was applied to a plastic plate with various roughness areas produced by machining the surface with sandpaper of different grain size, and liquid spreading was monitored for some time. The droplet volume was constant. The spreading time was recorded using a stopwatch. The spot diameter was measured using a caliper.

Figure 4 shows a plate with different roughness parameters and penetrant droplets applied.

Table 3 shows the experimental dependence of the penetrant spot spreading on the rough surface on time.

Figure 5 shows graphical interpretation of the results presented in the Table 3.

As can be seen from the graph, the larger the surface roughness parameter, the larger the liquid spot diameter.

The next stage was the penetrant testing performed on a plastic sample using a flaw detection kit. At the stage of removing excess penetrant from the test object surface, a false surface background occurred on the plate with the roughness area of $Rz = 30\ \mu m$. This can be attributed to the capillary effect, that is each groove of the rough surface was a capillary through which the liquid propagated, which can lead to unreliable test results.
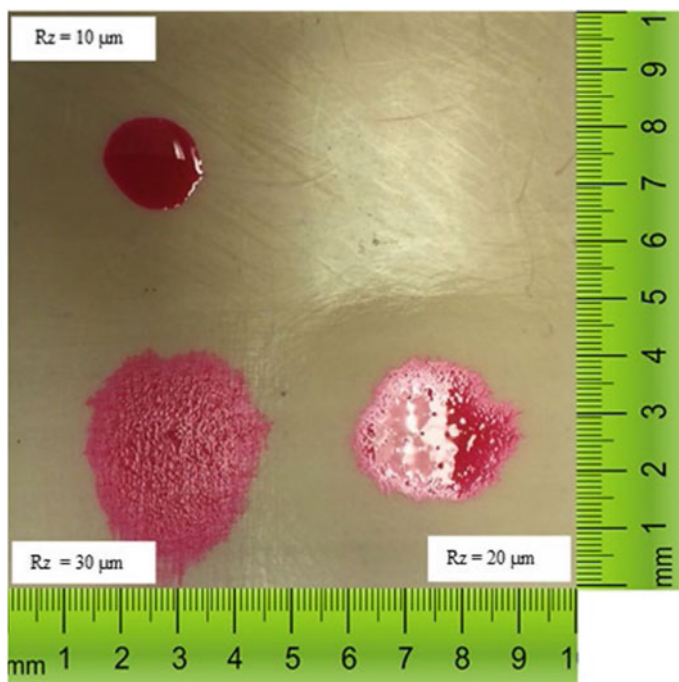
Fig. 4 Plate with penetrant droplets applied

D [mm] t [s]	Rz = 10 [μm]	Rz = 20 [μm]	Rz = 30 [μm]
1	9.7	9.9	11.2
3	12.2	14.5	14.6
5	13.6	17.0	17.0
7	14.6	18.9	18.9
10	15.4	20.9	20.8
15	17.1	22.8	23.3
20	18.4	24.1	25.3
30	19.9	26.1	28.0
50	21.7	28.9	31.5
80	23.8	31.4	35.0
120	25.9	33.7	38.9
200	29.8	36.3	42.4
300	31.9	38.8	45.3
360	33.5	40.7	47.4

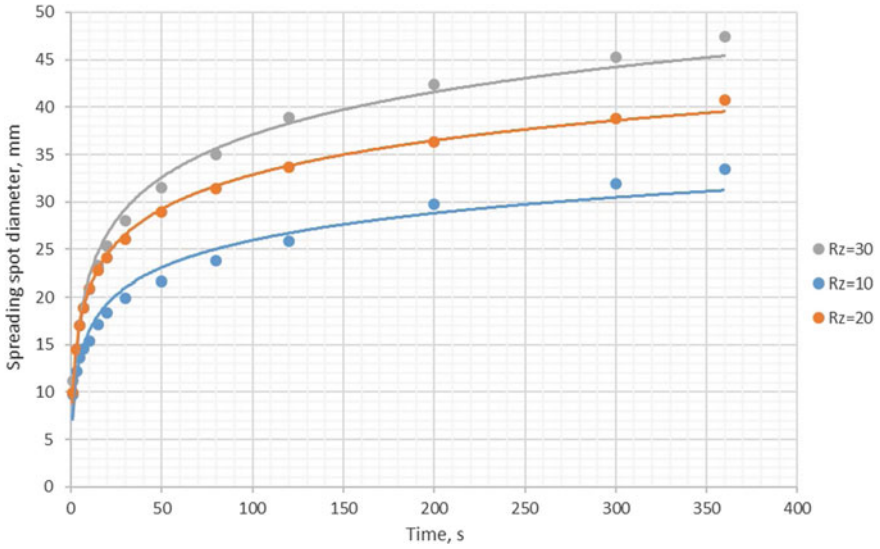**Table 3** Experimental dependence of the diameter of the liquid spot spreading on time

Fig. 5 Experimental dependence of the liquid spot spreading on time

After that, the modeling results were compared with the results of full-scale experiments of penetrant spreading on the rough surface.

The experimental results were statistically processed to determine the average value, standard deviation, and confidence interval. Figures 6, 7 and 8 present the graphs.
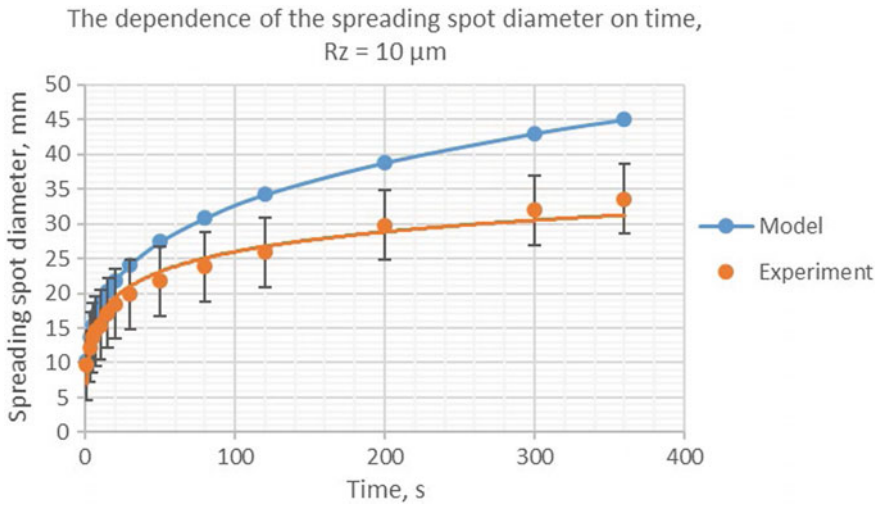

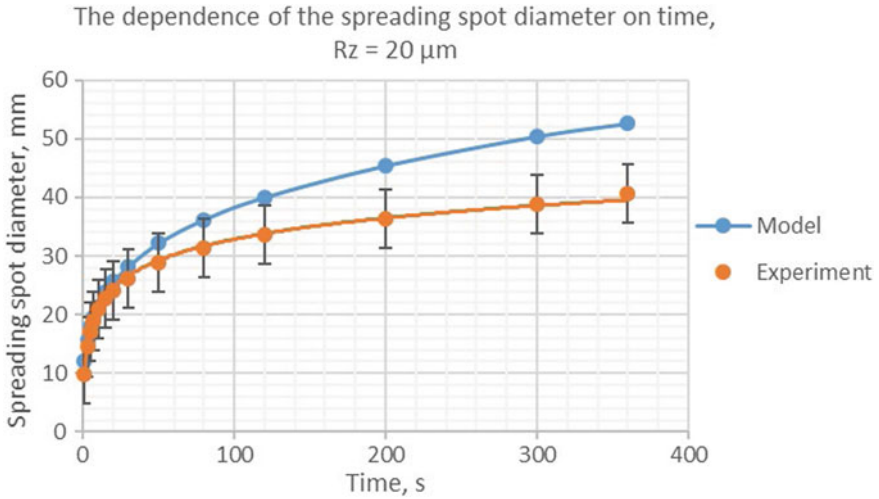**Fig. 6** Comparison of the modeling results with the experimental values at Rz = 10 μm

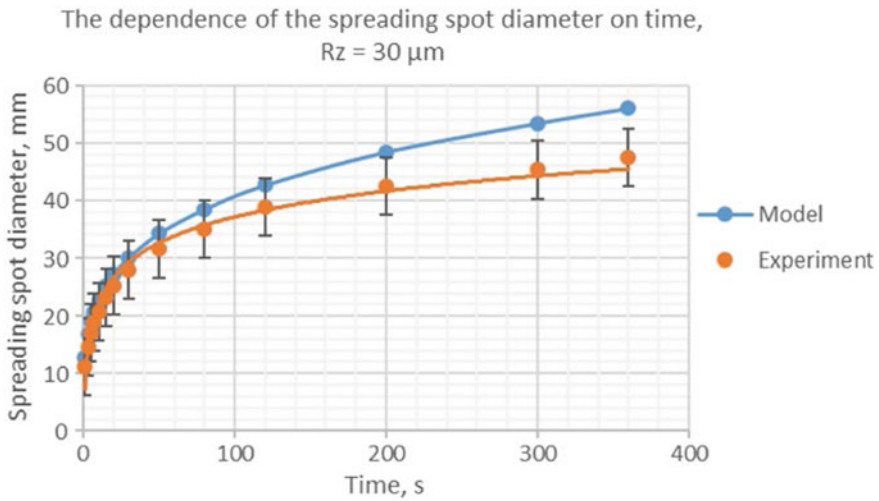**Fig. 7** Comparison of the modeling results with the experimental values at $Rz = 20$ μm

Fig. 8 Comparison of the modeling results with the experimental values at $Rz = 30$ μm

The curves obtained in modeling are within the confidence intervals, and thus they indicate the efficiency of the proposed mathematical model of liquid spreading on the rough surface at the initial stages of spreading.

5   Conclusion

Mathematical model of liquid spreading on the rough surface is based on the liquid spreading equation according to the hydrodynamic viscous mode.

Modeling of acetone-based penetrant spreading on a plastic plate with different surface roughness parameters is performed.

Efficiency of the mathematical model is confirmed experimentally.

Increase in the roughness parameter contributes to better liquid spreading on the surface.

Since each groove on the rough surface is a capillary through which liquid spreads, the penetrant cannot be completely removed from the surface at the stage of removing excess penetrant from the surface of the test object, which can cause invalid results of penetrant testing.

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