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**MATERIAL FACTORS IN RELATION TO DEVELOPMENT TIME IN LIQUID-PENETRANT INSPECTION. PART 3. TESTING OF MODEL PLATES**

The paper is the continuation of the previous ones entitled „Material factors in relation to development time in liquid-penetrant inspection. Part 1. Material factors” and „Material factors in relation to development time in liquid-penetrant inspection. Part 2. Investigation programme and preliminary tests” in which material factors influencing essentially the development time in penetrant testing as well as the range of their values have been specified. These factors are: material kind, surface roughness and imperfection width.

In the paper it has been described how far the development time in colour penetrant testing is influenced by an individual material factor. Moreover, it has been presented the equation being the function of material factors and development time.

*Keywords:* imperfection, defect, penetration testing, adhesion

**1. Introduction**

The paper is the continuation of the previous ones entitled „Material factors in relation to development time in liquid-penetrant inspection. Part 1. Material factors” and „Material factors in relation to development time in liquid-penetrant inspection. Part 2. Investigation programme and preliminary tests” in which material factors influencing essentially the development time in penetrant testing as well as the range of their values have been specified. These factors are: material kind, surface roughness and imperfection width [1,2].

Having made penetrant testing of the cracks arisen in the model plates and having obtained the values of the cracks width and the roughness of crack surfaces, it has been assigned three value levels to each above mentioned factor (independent variable) (Table 1).

TABLE 1

Factors subjected to testing and the levels assigned to them

Level of factor	Process: development time		
	Factors subjected to testing		
Independent variables	Factor related to material kind	Surface roughness, Ra, μm	Discontinuity width, μm
Lower level	1	1	50
Middle level	1,92	5	500
Upper level	3,4	10	1000

The value levels for the factor related to the material kind have been determined on the basis of differences in the devel-

opment time for particular structural materials. To this end the specimens of steel, aluminium and nickel have been prepared (Fig. 1).

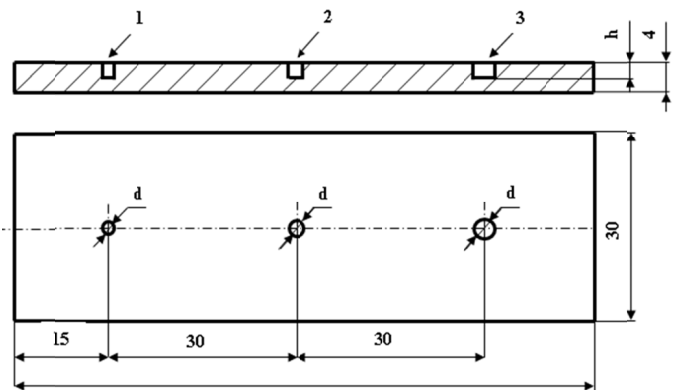


Fig. 1. Shape and dimensions of elements for testing by colour penetrant method, made of different structural materials, with holes simulating welding imperfections in the form of pores; 1, 2, 3 – designation of holes, d – hole diameter, h – hole depth

In the specimens designed for testing it was made blind holes simulating superficial pores, the same in dimensions as those in respective plates made of different materials. With a view to optimization of the penetrant testing process run, psychophysical abilities of the operator and measurement accuracy of indications only three holes were made in each element. Nominal dimensions of the holes are set up in the Table 2.

Next, it was made a series of penetrant tests according to the procedures described in the previous paper comparing

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simultaneously the development time for holes the same in dimensions but bored in different materials. Mean development times for the same holes but made in different materials are shown in the Fig. 2.

TABLE 2

Denotation of elements for penetrant testing, holes in the elements and their nominal dimensions

Ser. No.	Denotation of element	Denotation of holes in element	Nominal dimensions of holes	
			diameter „d”, mm	depth „h” <sup>1)</sup> , mm
1	STEEL	1	1,25	1,25
2		2	1,50	
3		3	1,75	
4	ALUMINIUM ALLOY	1	1,25	
5		2	1,50	
6		3	1,75	
7	NICKEL	1	1,25	
8		2	1,50	
9		3	1,75	

<sup>1)</sup> In relation to discontinuities (welding imperfections) the term „height” should be used but in consideration of comprehensibility of the paper contents, the term „depth” has been used.

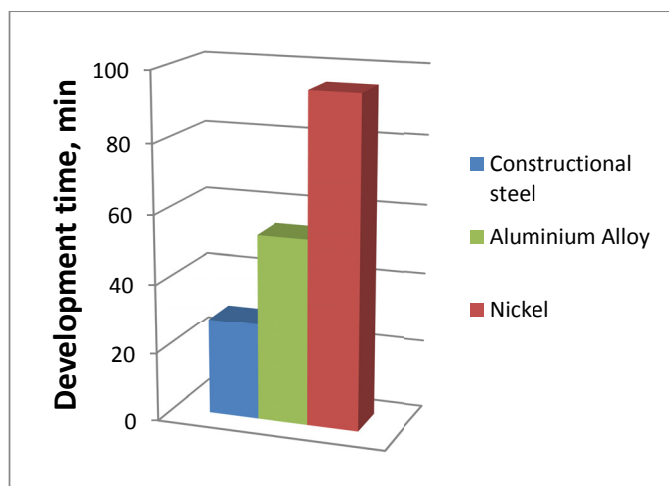


Fig. 2. Average development times for holes with the same dimensions but made in different structural materials

Owing to constant parameters such as surface roughness and dimensions of holes it was possible to determine the influence of the material kind on the development time. The results enabled to determine the proportion in development time between the test materials which is 1:1,92:3,4, for steel, aluminium alloy and nickel, respectively. The shortest development times were obtained for structural steel, the middle ones for aluminium alloy and the longest for nickel what is conformable to the previous practical testing (the paper „Material factors in relation to development time in liquid-penetrant inspection. Part 2. Investigation programme and preliminary tests”).

It was tried to catch the value related to the kind of material which affects the development time, namely adhesion. The adhesion occurring between the material under testing and the

penetrant is connected with the surface tension. The surface tension, in turn, is closely connected with the material kind and the roughness value of the machined surface. In order to obtain the model plates with specified values of the surface roughness it was applied the abrasive blasting which changed free surface energy and thus the surface tension. In the light of these facts the spreading test was useless because other results were expected on natural crack surfaces and other ones on the model plates. For verification purposes it was carried out spreading tests but, in accordance with suppositions, their results did not allow to connect, univocally, the spreading ability with the kind of material [3,4].

The levels of surface roughness values were averaged in such a way that they comprised the scope of all materials. The width of measured cracks for all materials ranged from 4÷1228 µm. While the range of cracks width was similar for structural steel and nickel, it was above twice as small for aluminium. Therefore, the width range of cracks assumed for above testing has been averaged so, that it includes the earlier results scope. The lower level of values is as much as 50 µm because of the limitation of the plate clearance gauge.

Having assigned three value levels to each variable it has been supplemented the factorial plan (Table 3).

TABLE 3

Factorial plan with values

Process no.	Experiment matrix		
	Factor related to the material kind	Surface roughness, µm	Discontinuity width, µm
1	1	1	50
2	1	5	1000
3	1	10	500
4	1,92	1	1000
5	1,92	5	500
6	1,92	10	50
7	3,4	1	500
8	3,4	5	50
9	3,4	10	1000

For the factorial plan it was made model plates of test steel, aluminium alloy and nickel. The roughness of their butting faces was on the lower, middle and upper level. The roughness of crack surfaces is similar both in transverse and longitudinal direction of the crack.

The required values of the roughness could not be obtained by means of machining because the required value was obtained in one direction only, whereas the roughness values differed even by several hundred percent in the perpendicular direction.

In this connection it was made abrasive blasting, whereas more precisely – sand-blast cleaning. Owing to the fact that it was made use of several parameters such as various abrasive material, its different granulation, various air pressure and nozzle diameter, the required values of butting faces roughness were obtained what was shown in the Table 4.

The sand blasting process was carried out on butting faces of plates, 240 × 60 × 6 mm in dimensions, selected for testing.

Before sand blasting the butting faces of the plates were milled thoroughly what enabled to obtain their perpendicularity and low roughness value. The sand blasting process was started from these initial parameters in order to be able to repeat the process of the surface preparation by milling, if any failure happens. As the failure of sand blasting process it was considered the excessive deviation from the required roughness value. It was assumed the following deviations as permissible:

- for  $R_a = 1 \mu\text{m} \pm 0,25 \mu\text{m}$ ,
- for  $R_a = 5 \mu\text{m} \pm 0,50 \mu\text{m}$ ,
- for  $R_a = 10 \mu\text{m} \pm 1 \mu\text{m}$ .

TABLE 4

Confrontation of measured surface roughness values in the model plates with expected results.

Material kind	S355J2C+N		AlSi1MgMn		Nickel 200	
	Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2
Required roughness value, $R_a, \mu\text{m}$	1		1		1	
Measured roughness value, $R_a, \mu\text{m}$	0,89	0,94	0,87	0,78	1,03	0,96
Required roughness value, $R_a, \mu\text{m}$	5		5		5	
Measured roughness value, $R_a, \mu\text{m}$	4,64	4,83	5,30	5,41	4,68	5,05
Required roughness value, $R_a, \mu\text{m}$	10		10		10	
Measured roughness value, $R_a, \mu\text{m}$	9,38	9,62	10,58	10,06	10,84	10,26

The roughness profile was measured for every butting face in 5 spots and then the result was averaged (Table 4). The surface roughness was measured in accordance with PN-EN ISO 4288:2011E recommendations. The elementary segment length,  $l_e$ , was 0,8 mm or 2,5 mm while the measuring length,  $l_m$ , was 4,8 mm or 15 mm, respectively. The elementary and measuring length values depend on the roughness range expected on the surface under measurement. Shorter elementary and measuring segments were used for the measurement of roughness near 1  $R_a$ , whereas longer ones for the measurement of roughness near 5 and 10  $R_a$ . In the final effect the width of the model plates was reduced from 60 mm to 46-55 mm.

In the Fig. 3 it is shown the comparison of butting faces of the plates with different roughness.

The next stage after preparation of butting faces of the model plates was careful degreasing them and washing in ultrasonic wash stand. After drying of the model plates, the gap showing the crack width was established between them on the lower, middle or upper level (according to the experiment programme). The plates were set up in the device as it is shown in the Fig.4. Under them, flat steels, 4 mm in thickness, were put in

order to avoid touching the background by the plates. It allows to show better the real testing conditions.

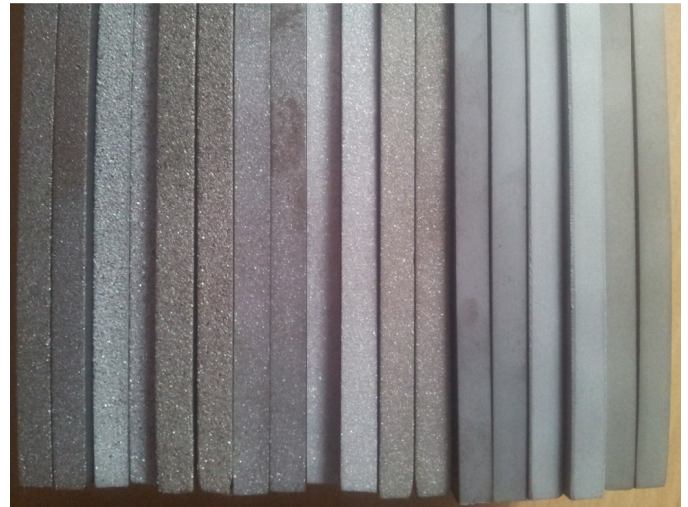


Fig. 3. View of plates after sand blasting. From the left: 6 plates, 10  $R_a$  in roughness, 6 plates, 5  $R_a$  in roughness and 6 plates, 1  $R_a$  in roughness



Fig. 4. Testing device in which the model plates were placed



Owing to the side bolts, the width of the gap was adjusted while its value was measured by means of the plate clearance gauge. On the model plates prepared in such a way, the penetrant was applied by brush. The penetrant quantity was determined experimentally; namely the brush was sprinkled by the penetrant and at the moment when the penetrant began to flow down from the brush, it was put onto the gap set up between the plates. To ensure the repeatability of results this action was carried out twice: once by moving the brush from one side to the other and later backwards. The smallest and the largest width of indications were recorded (Fig. 5) until the growth of indications stopped.

## 2. Results

On the basis of the previous tests it was established the penetration time, namely 30 minutes for steel and aluminium; 120 minutes for nickel. The tests were repeated three times and their results were averaged. The final results are shown in the Table 5.

## 3. Analysis of testing results

The results were analysed in the STATISTICA software which is provided with tools for planning the factorial experiments as well as for analysis of their results. It was made use of the module „Diversified regression” by means of which quan-



Fig. 5. Growth of indications on model plates

TABLE 5

Final results of factorial plan

Process no.	Test no. 1		Test no. 2		Test no. 3		Average from 3 tests	
	<i>b</i> , mm	<i>t</i> , min	<i>b</i> , mm	<i>t</i> , min	<i>b</i> , mm	<i>t</i> , min	<i>b</i> , mm	<i>t</i> , min
1	54,5	220	56	245	54,5	225	55	230
2	72,5	420	73	430	70,5	410	72	420
3	68	395	66,5	360	66,5	385	67	380
4	53	405	57	425	55	400	55	410
5	61	490	58	485	61	525	60	500
6	54	400	52,5	385	52,5	385	53	390
7	67	435	70	465	70	450	69	450
8	71,5	380	71	375	73,5	400	72	385
9	106	730	100	690	100	710	102	710

Note: The sequence of actions – in accordance with the Table 3. *b* – dimension of the greatest indication; *t* – development time after which the growth of indications has stopped.

titative formulation of the relations between many independent variables and the dependent variable was possible.

Before making the regression analysis it was made the series of correlations of particular variables. This resulted from two reasons: firstly – checking if the predictors correlate with the variable *Y*, and secondly – checking if they do not correlate between themselves. The results of correlation are shown in the Fig. 6.

It results from the above mentioned correlations that each independent variable correlates with the dependent variable, i.e. with the development time what is confirmed by the values shown in the above presented figure (0,575008; 0,438465; 0,602459). Independent variables, however, do not correlate between themselves what is also the desired result.

After obtainment of the positive result of the correlation between independent variables it was formulated the equation

Variable	Correlations (Sheet1)			
	Factor related to material kind	Roughness, Ra	Gap width, $\mu\text{m}$	Development time, min
Factor related to material kind	1,000000	-0,000000	0,000000	0,575008
Roughness, Ra	-0,000000	1,000000	0,000000	0,438465
Gap width, $\mu\text{m}$	0,000000	0,000000	1,000000	0,602459
Development time, min	0,575008	0,438465	0,602459	1,000000

Fig. 6. Correlation between independent variables

of diversified regression on the basis of results of 9 tests shown in the Table 3.

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + e \quad (1)$$

where:

- $y$  – development time, min,
- $x_1$  – factor related to material kind,
- $x_2$  – surface roughness, Ra
- $x_3$  – discontinuity width,  $\mu\text{m}$ ,
- $e$  – random component.

The model parameters are the numbers  $b_0, b_1, b_2, b_3$ , while  $b_0$  is the point of intersection of the straight line with the Y-axis,

whereas  $b_1, b_2$  and  $b_3$  are slopes of the straight line, i.e. the measure of the line slope in relation to the X-axis. The random component,  $e$ , shows random interferences of functional relation between values of the dependent variable and values of independent variables. This component expresses the influence of all factors which, apart from independent variables, can affect the considered Y variable. It is connected with lack of full matching of the analytical form of the regression function to the real relations between the variables being analysed. The random component allows to calculate the accuracy of the assessment of parameters of the line regression function. The results shown in the Fig. 7 have been obtained after making the regression.

Summary of regression of dependent variable: Development time, min (Sheet 1)						
R= ,94119244 R^2= ,88584321 Popraw. R2= ,81734914						
F(3,5)=12,933 p<,00860 Standard estimation error: 54,548						
N=9	b*	Bt. std. z b*	b	Bt. std. z b	t(5)	p
<b>W. free term</b>			110,1518	55,78205	1,974682	0,105292
Factor related to material kind	0,575008	0,151100	69,9876	18,39131	3,805469	0,012558
Roughness, Ra	0,438465	0,151100	14,3306	4,93850	2,901812	0,033719
Gap width, $\mu\text{m}$	0,602459	0,151100	0,1868	0,04686	3,987143	0,010456

Fig. 7. Summary of regression of dependent variable: Development time

The purpose of this work was to find, among other things, the regression coefficients shown in the column 4 in the Fig. 7. In the first line there is the constant  $b_0$ , while in the second, third and fourth line there are the coefficients  $b_1, b_2, b_3$ . After the substitution of the regression coefficients it has been obtained the following equation:

$$y = 110,1518 + 69,9876 \cdot x_1 + 14,3306 \cdot x_2 + 0,1868 \cdot x_3$$

The  $b_1$  parameter is 69,9876, what means that if the change of material from steel to aluminium occurs, it is expected that the development time will increase by about 64 min (proportion 1:1,92), whereas the change from steel to nickel will increase the development time by about 168 min (proportion 1:3,4). The  $b_2$  parameter, however, is 14,3306, what means that if the surface roughness value increases by one unit (in this example by 1 Ra), then it is expected that the development time would increase by 14,3306 min. The  $b_3$  parameter, in turn, is 0,1868, what means that if the value of the discontinuity width increases by one unit (in this work by 1  $\mu\text{m}$ ), then it is expected that the time of development would increase by 0,1868 min.

In practice, the complete information about all possible tests is not available, therefore it was obtained the regression function computed by the least square method basing oneself on the data from nine tests comprising the whole range of independent variables.

This regression function, called empirical one, is the approximation of regression in all possible events. It is connected with the problem of the assessment of divergence between values of the dependent variable „y” and the values calculated from the model. The differences which describe this divergence are called remainders. The smaller the remainders are, the nearer to the empirical value  $y$  the values anticipated by the model occur. It would be ideally, if the remainders were equal zero, but it is impossible in practice. Therefore, it was decided to consider the standard deviation of the remainders, „e”, as the measure of the described divergence. In the statistics, the precision of the estimator is shown by its variance. It is so in fact – this value called the standard estimation error and marked as  $Se$  gives the information about the average value of empirical deviations of the dependent variable from values calculated from the model (theoretical ones). Owing to this parameter, the measure of the

results dissipation around the regression line is known. So, the standard deviations of the remainders shows the degree of „matching” of the model to the empirical data. The smaller  $Se$ , the better matched model. This value is shown in the Fig. 7 and amounts to 54,548.

It means that the predicted values of the development time are different from the empirical ones by about 54,54 min., on average. Therefore, the final form of the equation is as follows:

$$y = 110,1518 + 69,9876 \cdot x_1 + 14,3306 \cdot x_2 + 0,1868 \cdot x_3 \pm 54,54$$

The calculated regression coefficients  $b_0$ ,  $b_1$ ,  $b_2$  and  $b_3$  are the estimation of regression coefficients for all possible events. They are strained by the error which determines the mean error of the parameter estimation. It is the estimation of the mean divergence between the model parameters and their possible assessments. Of course, the smaller mean estimation error, the better situation is. These values are shown in the result sheet (Fig. 7) in the column no. 5:

- assessments of the  $b_0$  parameter deviate from it by  $Sb_0 = 55,78205$ ,
- assessments of the  $b_1$  parameter deviate from it by  $Sb_1 = 18,39131$
- assessments of the  $b_2$  parameter deviate from it by  $Sb_2 = 4,93850$
- assessments of the  $b_3$  parameter deviate from it by  $Sb_3 = 0,04686$ .

When estimating the slope of the straight line  $b_1$  on the level 69,9876, it was mistaken by about 18,39131, on average. Next, when estimating the slope of the straight line  $b_2$  on the level of 14,3306, it was mistaken by about 4,93850, on average. In turn, when estimating the slope of the straight line  $b_3$  on the level of 0,1868, it was mistaken by about 0,04686, on average. Similarly, while estimating the free term on the level of 110,1518, it was mistaken by about 55,78205, on average. The estimation error for the parameter  $b_1$  is about 26% ( $18,39131/69,9876 = 0,26$ ), while for the parameter  $b_2$  – about 34% ( $4,93850/14,3306 = 0,34$ ), and for  $b_3$  – about 25% ( $0,04686/0,1868 = 0,25$ ). For the free term, however, the estimation error is the largest, namely it is about 50% ( $55,78205/110,1518 = 0,50$ ). If the error value is near 100% or more, the precision is very unsatisfactory. The values above 50% should already call attention onto the other assessments of the model. Here only the free term strays from the expected results. It can show that there are more independent variables which have a decisive effect on the development time, e.g. the quantity of the developer applied.

The above mentioned mean errors of the estimation are shown also in the window of results (Fig. 7) in the column 6. These are quotients  $t$  ( $t = b/Sb$ ). Now it is seen clearly that the first parameter is estimated 3,80 times more than the error of estimation while the second – 2,90 and the third – 3,98. Only for the free term it is a small value, namely 1,97.

The another result for interpretation is the coefficient of determination. It is the number  $R^2$  from the interval  $<0, 1>$ .

If  $R^2$  is equal 1, it means perfect matching, whereas  $R^2 = 0$  means lack of connection between variables. The coefficient of determination shows which portion of the total variation of dependent variable is explained by the line regression. The  $R^2$  value is given in the sheet of results (Fig. 7) – in the upper line. It is 0,8858. So, the equation of diversified regression explains 88,58% of observed variation but it does not explain 11,42%. The larger  $R^2$  is, the better is the description of the dependent variable by the equation. Addition of the next variable to the existing model would result in the increase in  $R^2$  value but the purpose of this investigation is to find the relations between independent variables and the dependent variable. Often, in practice, it is applied rather so called corrected  $R^2$  in which it is taken into account that  $R^2$  is calculated from an experiment and can be charged with an error if the results are generalized onto all possible events. The corrected  $R^2$  shows how well this regression equation would be matched to another test with the same variables. The corrected  $R^2$  is 0,8173 what is also a satisfactory result.

The next step in the analysing of the obtained model is its verification. To this end, the diagrams of results spread for the function of the development time vs. each independent variable have been created (Figs. 8-10). It is seen in the Fig. 9 that the development time is the shortest for steel, the intermediate for aluminium and the longest for nickel. That is to say, the earlier practical tests carried out under this work have been confirmed.

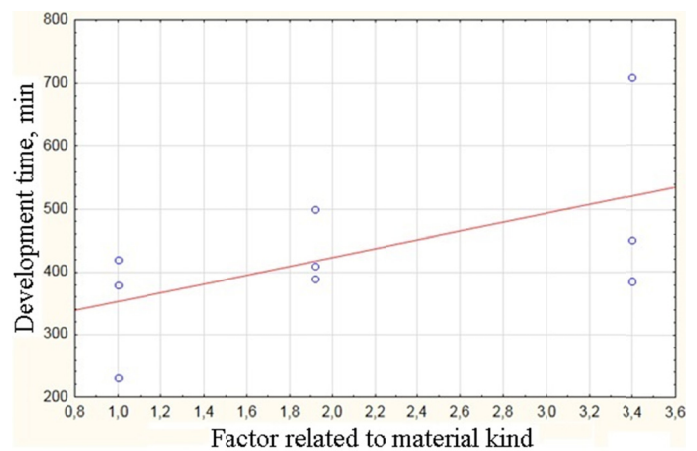


Fig. 8. Influence of the material kind on the development time in penetrant testing.

Indications on the horizontal axis: 1 – steel; 1,92 –aluminium alloy; 3,4 – nickel

In the next diagram (Fig. 9) it is shown the relationship between the roughness of the surface of the gap to which the penetrant gets in and the development time. It can be noticed that the development time becomes longer when the roughness is increasing. It was expected that the larger surface roughness would cause slower flowing out of the penetrant onto the surface and by the same the longer development time.

In the Fig. 11 it is shown the relationship: development time vs. gap width. Together with the increase in the gap width, the development time gets longer. This was also the expected



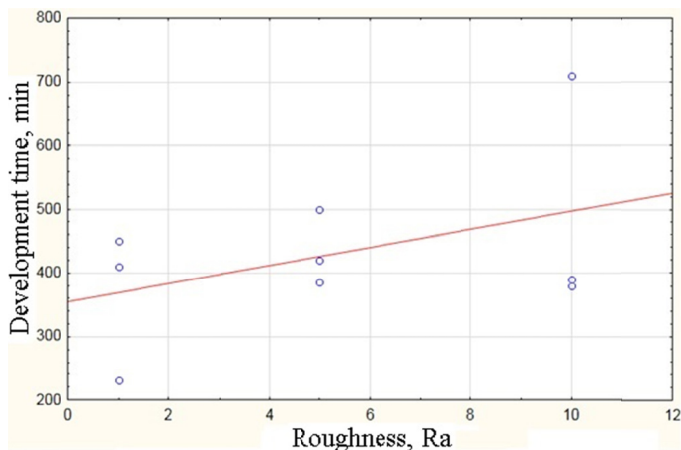


Fig. 9. Influence of surface roughness on the development time in penetrant testing

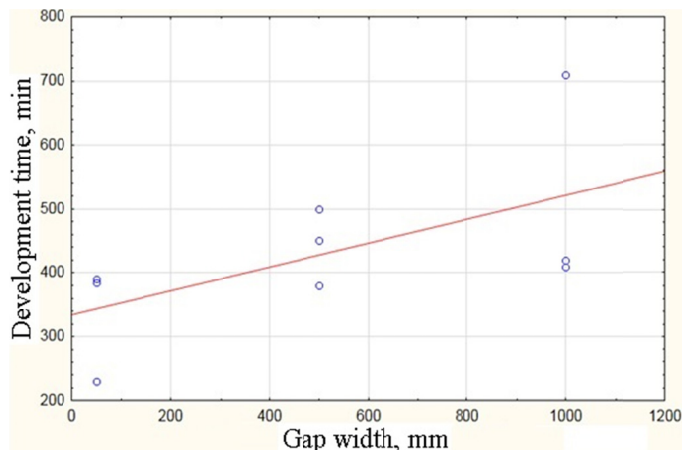


Fig. 10. Influence of discontinuity width on the development time in penetrant testing

result because the volume of the penetrant in the gap increased for that reason.

All three independent variables gave positive results. In the equation of diversified regression they have positive signs, what is also correct, because it confirms theoretical assumptions.

Apart from verification concerning essential facts, also the statistical one was carried out. Among from many methods en-

abling to make this analysis several fundamental ones have been chosen. Even as early as before the beginning of the diversified regression it was checked the correlation of parameters (Fig. 6). It was also checked these t values which are above 1 (Fig. 7, column 6) what is the evidence of the gravity of independent variables. Additionally the excess of independent variables was checked (Fig. 11).

Variable	Excess of independent variables; DV: Development time, min; the column „square of R” includes the square of R for suitable variable with all the other independent variables				
	Tolerance	Square of R	Partial correlation	Semipartial correlation	
<b>Factor related to the material kind</b>	1,000000	0,00	0,862176	0,575008	
Roughness, Ra	1,000000	0,00	0,792109	0,438465	
Gap width, μm	1,000000	0,00	0,872201	0,602459	
	1	2	3	4	

Fig. 11. Window with calculated indices of an excess

In the Fig. 12 there are shown the calculated values of the following coefficients:

- the column 1 is the tolerance for the particular variable. The tolerance is equal  $1 - R^2$ . The lower is the tolerance for the particular variable, the more excessive is its share in the regression equation. It means that it is useless in comparison to the share of the other ones. If the tolerance is equal (or very near) zero, the coefficients of regression equation can not be calculated. However, in case under consideration, the tolerance of the variable amounts to 1, what is the evidence of lack of an excess in variables;
- column 2 is the  $R^2$  value between the variable under consideration and all the other independent variables. This index shows how much the variability of considered variable is explained by the other variables. The near is to the unit, the more excessive is the variable. In this case the values are equal zero, i.e. none variable is dependent on the other one;
- column 3 is the partial correlation between the variable under consideration and the dependent variable, i.e. development time. In case under discussion the following three

features are assessed simultaneously: roughness, gap width and material;

- column 4 is semipartial correlation between the variable under consideration and the dependent variable. This is the correlation of the independent variable with regard to connections with all the other variables and original dependent variable (without taking into account its correlations with the other variables). The values are high, then correct, as much as possible.

The final stage of the regression analysis is making use of the designed and verified model for forecasting of development time. The prediction of dependent variable serves this purpose. By means of that it was calculated the forecast development time for aluminium alloy, 1 Ra in roughness and 1200 μm in discontinuity width.

The equation assumes the following form:

$$y = 110,1518 + 69,9876 \cdot 1,92 + 14,3306 \cdot 1 + 0,1868 \cdot 1200 = 483,018592 \text{ min}$$

The presented result is burdened by the error which can originate both from the uncertain estimates and randomness of position of points in relation to the regression line. The result was verified by penetrant testing on model plates with considered parameters. The mean development time from among three tests was 445 min., what shows relatively low divergence between the forecasted development time and the real one.

The verification concerning the substance as well as statistical one allowed to check the significance of the whole model and

its parameters. The dependent variable is intensively affected by all independent variables while they do not correlate between themselves.

It was done also the diversified regression equation for the width of indication. The obtained results are of poor precision (Fig. 12), however, because the errors of estimation of b coefficients achieve even above 100%. For that reason the further analysis of the relation of indication width vs. independent variables was abandoned.

Summary of regression of dependent variable: Width indication (Sheet 4)							
R= ,71266948 R^2= ,50789779 Popraw. R2= ,21263647							
F(3,5)=1,7202 p<,27782 Standard estimation error: 15,182							
N=9	b*	Et. std. z b*	b	Et. std. z b	t(5)	p	
<b>W. free term</b>			32,06983	16,68642	1,921912	0,112652	
Roughness, Ra	0,383197	0,313720	1,67896	1,37455	1,221461	0,276357	
Gap width,	0,536831	0,313720	0,02232	0,01304	1,711177	0,147733	
Material	0,269945	0,313720	5,33333	6,19820	0,860465	0,428854	

Fig. 12. Summary of regression of dependent variable: indication width

It was tried to catch the relation between physical and chemical properties of the test materials, on one hand, and adhesion with penetrant, on the other, what means the differentiated development times. The adhesion phenomenon is affected by many factors and its theory still is not explained univocally [5-11]. The surface energy of metal (Table 6) influences essentially the adhesion between metal and penetrant though it can be changed by the abrasive blasting [4-6].

TABLE 6

Surface energy of selected metals in liquid and solid state

Material kind	Surface energy, mJ/m <sup>2</sup>	
	In liquid state	In solid state
Iron	1865	2090
Aluminium	850	914
Nickel	1770	1820

In this connection it cannot be precisely stated which physical property influences the development time most essentially. However, on the basis of both practical testing and that made on the model, it was found that the development time became longer depending on the material kind, in accordance with the developed diversified regression equation.

#### 4. Conclusions

On the basis of the test results analysis the following conclusions have been formulated:

1. It exists the relationship defining the development time and being the function of material factors. The form of this function is as follows:

$$y = 110,1518 + 69,9876 \cdot x_1 + 14,3306 \cdot x_2 + 0,1868 \cdot x_3 \pm 54,54$$

2. Each of the tested factors influences radically the development time in penetrant testing. The evidence of this is the correlation between independent variables and the dependent variable which is 0,575008 for the kind of material (in the experiment programme it is the factor related to the kind of material), 0,438465 for the surface roughness and 0,6024590 for the gap width. So, the gap width and the material kind influence most effectively the development time whereas the influence of the surface roughness is smaller but also very essential.
3. Together with the increase in the gap surface roughness the development time becomes longer. When the roughness increases by 1 Ra, the development time grows longer by about 14 minutes, on the average.
4. Together with the increase of the discontinuity width the development time becomes prolonged. Probably it results from the fact that the larger volume of the penetrant can get into the gap. If the discontinuity width increases by 1  $\mu\text{m}$ , the development time becomes prolonged by about 0,18 minute, on the average.
5. Material kind (in the experiment programme: the factor related to the kind of material) influences substantially the development time what was appeared as early as in the practical test stage. The differences in development times obtained in the experiment programme are similar to those obtained in practical tests. The shortest development time is for steel. For aluminium it is longer by about 64 minutes, whereas for nickel it is longer even by 168 minutes relative to steel. During conventional tests (the penetrant and developer are brought on one side) the development time



should not be longer than 60 minutes in case of steel. For aluminium and its alloys it should be about 200 minutes, whereas in case of nickel and its alloys it should be even about 230 minutes.

6. The development times for particular materials in testing of model cracks became prolonged considerably in comparison to those obtained in practical testing. Probably it was caused by the fact that in practical testing the cracks were in the form of closed capillaries while in testing of model cracks, assumed in the experiment programme, they were open capillaries.
7. The practical tests have shown that the penetration time in case of steel, aluminium and its alloys can be only 10 minutes. Longer penetration time does not affect the results. For nickel and its alloys, however, it is recommended to prolong the penetration time even to 120 minutes, because it influences both the development time and the indications value. Also for austenitic steels it is recommended to prolong the penetration time according to the percentage of nickel in their composition.
8. The obtained equation of diversified regression does not explain about 11% of variability what can be an evidence that there is another one or several independent variables which affect the development time, for instance quantity of brought developer or temperature.

### 5. Summary

It has been developed the methodics of testing and explained the relationship between the roughness of discontinuity surface, discontinuity width and kind of material (in the experiment programme: the factor related to the kind of material), on one hand, and the time of development, on the other, in penetrant testing. The investigations allowed to determine the directions of further testing related to this subject, namely penetrant testing of another materials, application of another testing techniques and checking of the influence of another variables on the development time, e.g. temperature, crack depth or quantity of developer.

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