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# The Influence of Surface Abrasion Treatment on the Properties of Substratum

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The strength of adhesive joints is in high dependence on real contact surface between the adhesive and substrate. The size of real contact surface depends not only on the geometrical parameters of substrate, but on the surface roughness, also. In order to find out quantitative relation between the substrate surface roughness and the shear strength of adhesive joints statistical parameters such as average surface roughness and standard deviation were calculated. It is shown that they depend on the substrate profile correlation function.

The expression of correlation functions, their coefficients and profile characteristics in dependence on the substrate abrasion treatment direction has been investigated. The possibility to predict properties of adhesive joints is discussed.

The expression of correlation function is independent on the substrate abrasion treatment direction.

*Keywords*: abrasion treatment direction, surface roughness, correlation function, strength of adhesive joints.

## INTRODUCTION

At the moment there are no theoretical models describing interrelations between adhesion, physical properties of the adhesive and substrate, and the practical strength of the adhesive bond. Rather, the literature on adhesion consists of many articles addressing specific areas of adhesion phenomena. A number of theoretical models that are specifically related to certain observed phenomena are used to explain them and all of them are contributed to predict bond strength [1].

According to the mechanical theory of adhesion a criterion of obtaining high adhesion is to provide a surface with a micromorphology and to provide an adhesive with low enough viscosity to completely fill the surface features. Obviously, surface roughness there is of great importance. The reason of that are not only interlocking effect, but the physical area of contact, also. It is accepted that the increase of surface area leads to the increase of total energy of surface interactions [2]. Surface roughness increases the plastic deformation of the adhesive in the interphase, resulting in the increase of joint strength [1 – 4].

Practically, the changes in contact surface area can be achieved by surface abrasion treatment. Different grades of abrasive paper produce various degrees of roughness on the substrate surface. Roughening increases the surface area for effective bonding and removes contaminants from the surface [1]. As a rule, abrasion direction is always normal to the loading direction. However, only several experimental studies were found on the effect of varying the linear direction of the abrasion process with respect to the loading direction.

In order to evaluate a real surface area as a function of surface roughness statistical characteristics are calculated. All these characteristics are the correlation function of the profile [5 – 8].

This work was concentrated on the finding out the main parameters of profile correlation function in dependence on the surface texture in order to obtain more clear dependence between surface roughness and bond strength and create fundaments for adhesion properties prognosis.

## EXPERIMENTAL

For investigation monolithic butadiene-styrene rubber was selected as a substrate. The density and hardness according to Shore scale was $\rho = 0.25$ g/cm$^3$ and $H = 75$, respectively.

The solvent - based poly-2-chlorobutadiene (mercaptane modified) rubber Baypren 330 (producer is Bayer AG, Germany) was used as adhesive. The solid content of prepared solution in mixture of organic solvents (ethylacetate: benzine = 3 : 2) was 20 %.

To produce rough rubber surface, abrasive paper of grade number No 60 was used. Test pieces in size of $80 \times 25$ mm$^2$ were abraded at five different angles, i.e. 0, 30 45, 60 and 90° with respect to the loading direction as shown in Fig. 1. The abrasion was performed on the abrasion machine, which contains special device for applying constant pressing force between specimen and abrasion disk.

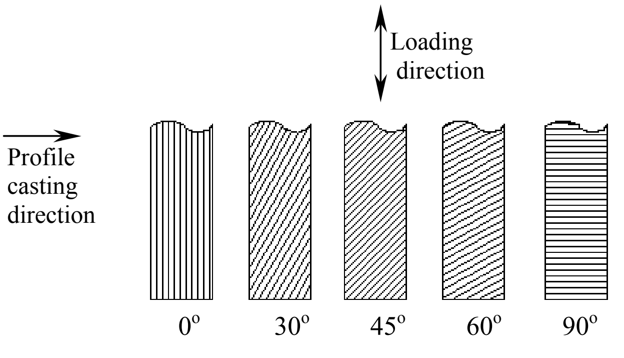

**Fig. 1.** Characteristic direction of surface roughness in dependence on the abrasion direction

The profile of abraded surface was analysed perpendicular to the loading direction (Fig. 1).

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The adhesive joints for lap shear tests were prepared from butadiene styrene rubber strips with working surface abraded in different directions. The dimensions of operating area were $10 \times 20$ mm. Adhesive was applied manually by a brush on the both rubber substrates two times and left to dry for 30 and 60 min for the first and second time, respectively. After this, the adhesive film was heat reactivated in the field of IR rays at 90 °C for 60 s in order to facilitate the interlocking of composition surfaces applied to the two identically bonded rubber strips. Then the strips were placed in contact and pressure of 0.25 MPa was immediately applied for 60 s to achieve a suitable joint.

The adhesive bond strength was evaluated according to the results of lap shear tests on the testing machine FP 10/1 (Germany) at peel rate 0.1 m/min. The values of strength were obtained as the average of six tests. The initial and final peel strength was measured respectively after 60 s and 24 hours two substrates were joined.

## RESULTS AND DISCUSSION

**Experimental results.** Fig. 2 shows the irregular profiles produced after abrasion of sample surface in various directions. One can see, that the increase of angle between the surface abrasion and loading direction, decreases the distance between highest profile peak and the deepest profile valley of real profile length $l$.

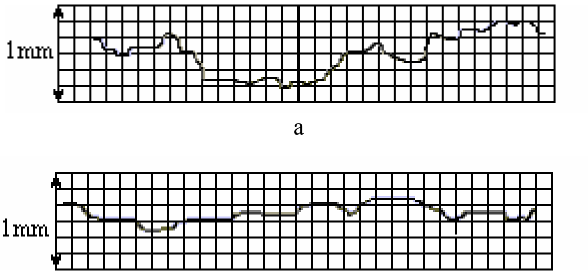

**Fig. 2.** Substrate surface profiles for different abrasion treatment direction $x$, degrees: a – 0, b – 60

For more clear representation of the obtained results the increment of real profile length $\Delta l$ was calculated. It was assumed as a difference between geometrical and real profile length. Results presented in the Table 1 indicate that increase of angle of abrasion direction results on the decrease of real profile length values and indicates decrease of real contact surface area, also.

**Table 1.** The increment $\Delta l$ of real profile length in dependence on abrasion direction

| Abrasion treatment direction, $x$ ° | $\Delta l$, μm |
|---|---|
| 0 | 0.2817 |
| 30 | 0.1636 |
| 45 | 0.0968 |
| 60 | 0.0211 |
| 90 | 0.0153 |

The influence of abrasion direction on the adhesion properties changes was evaluated according to the results of shear lap tests, which are presented in Table 2. These results suggest that increase of the angle of abrasion direction with respect to the loading results on the increase of possibility for mechanical interlocking. It increases the level of practical adhesion even substrate and adhesive is identical in all cases. These results indicate that the highest shear strength values can be reached when surface abrasion direction is perpendicular to the tension direction.

**Table 2.** The results of shear lap tests in dependence on surface abrasion direction

| Abrasion treatment direction, $x$ | Shear lap stress, MPa |
|---|---|
| 0 | 38.1 |
| 30 | 39.0 |
| 45 | 39.8 |
| 60 | 40.5 |
| 90 | 42.0 |

**Statistical analysis.** Results of statistical approximation of surface roughness parameters such as average of surface roughness and standard deviation for the all obtained profiles are presented in the Table 3. One can see, that changes of abrasion treatment direction $x$ from 0 up to 90 degrees leads to the decrease of its values.

**Table 3.** The main statistical characteristics of profile in dependence on abrasion treatment direction

| Abrasion treatment direction, $x$ ° | Average of surface roughness | Standard deviation of surface roughness |
|---|---|---|
| 0 | 0.445 | 0.266 |
| 30 | 0.329 | 0.217 |
| 45 | 0.287 | 0.179 |
| 60 | 0.213 | 0.122 |
| 90 | 0.196 | 0.109 |

It is known that abrasive roughened rubber surface form profile, which statistically can be presented as realisation of fixed function with normal distribution. Earlier it was determined that surface roughness of substrate can be approached as realization of stationary normal process, which main characteristic is correlation function [5 – 7]. This function shows correlation between initial experimental data (in this case randomly selected profile zone, which length characterize parameter $\tau$) and those moved in some interval data sequence coefficient.

Empirically correlation function of roughened rubber surface, which abrasion treatment is perpendicular to the loading direction can be described according to this relation [5, 6]:

$$K(\tau) = \frac{C}{1 + (\alpha \cdot \tau)^2}, \tag{1}$$

where $\tau$ is the surface length parameter, $C$ and $\alpha$ are the coefficients of correlation function determined by the method of least square.

Experimentally obtained different profiles were used to find out values of correlation function coefficients *C* and $\alpha$. As later will be shown values of these coefficients and correlation function influence on the empirical expression of real profile length $l$.

In order to obtain correlation function in dependence on abrasion treatment direction profiles of butadiene styrene rubber surfaces were investigated. It was determined that changes in abrasion direction do not influence on the earlier obtained expression of correlation function $K(\tau)$ (Eq. 1). Only the variability of both coefficients *C* and $\alpha$ is influenced. Values both of them are presented in Table 4.

**Table 4.** Values of correlation coefficients of Eq (1) in dependence on abrasion direction

| Abrasion treatment direction, $x$ ° | Coefficients | |
|---|---|---|
| | *C* | $\alpha$ |
| 0 | 0.071 | 0.063 |
| 30 | 0.047 | 0.059 |
| 45 | 0.032 | 0.055 |
| 60 | 0.015 | 0.070 |
| 90 | 0.012 | 0.106 |

As presented in Fig. 3, the increase of angle between abrasion and loading directions results in the decrease of correlation function values. More significant differences and increase of plots slope with decrease of abrasion direction was observed in the zone of narrow interval $\tau$ (0 – 30). These results indicate that decrease of abrasion treatment direction require wide interval $\tau$ in order to achieve similar function $K(\tau)$ values.

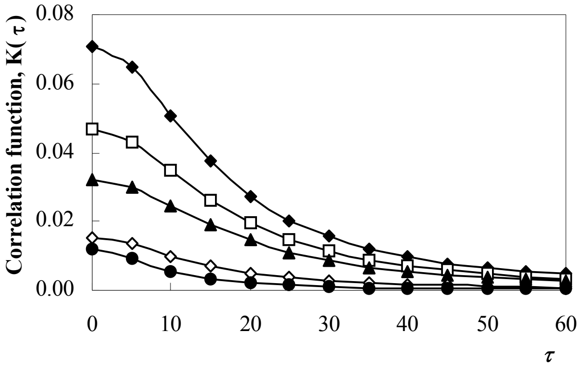

**Fig. 3.** The changes of correlation function $K(\tau)$ in dependence on abrasion direction $x$,: ♦ – 0, □ – 30, ▲ – 45, ◊ – 60, ● – 90

The analysis and approximation of experimental results showed that independently on the abrasion treatment direction $x$ correlation function coefficient *C* changes according to this empirical equation:

$$C(x)=(C_0-C_{90})\cdot\cos\left(\left(\frac{13\pi}{18}-\frac{2}{\pi}\left(\frac{13\pi}{18}-1\right)x\right)x\right)+C_{90}, \quad (2)$$

where $C_0=C\big|_{x=0^0}$ and $C_{90}=C\big|_{x=90^0}$ are values of the coefficient *C* determined for samples treated in abrasion direction of 0 and 90 degrees, respectively.

The experimental values of coefficient *C* and those calculated according to the Eq. 2 are presented in Fig. 4. Correlation between these data was 0.997.

The second step was to find out empirical expression of real profile length $l$, which allows to evaluate the size of the real contact surface area.

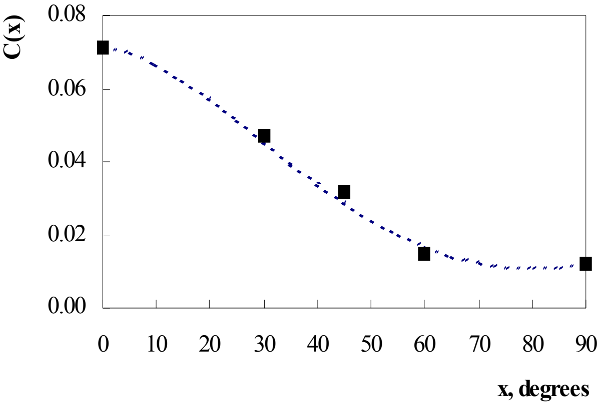

**Fig. 4.** The variation of correlation function (Eq. 2) coefficient *C*: ---- – theoretical curve, ■ – experimental points

Real profile length $l$ can be expressed as a function, which is interrelated with the second fluxion of the earlier obtained correlation function $K(\tau)$:

$$l=\begin{cases}1+\frac{1}{2}\sigma^2-\frac{9}{24}\sigma^4+O(\sigma^6) & ,\sigma<<1\\ \frac{-\log(\gamma/8\sigma^2)}{\sqrt{2\pi}}\left(\frac{1}{2\sigma}+\frac{1}{16\sigma^3}+O(\sigma^{-5})\right) & ,\sigma>>1\end{cases}, \quad (3)$$

where $\gamma=e^{0.5772}$, $\sigma^2=-K''(0)$, $O(\sigma^6)$ is decline value.

It was determined that structure of Eq. 2 also fulfils relation between the real profile length and surface abrasion direction and can be written as:

$$l(x)=(l_0-l_{90})\cdot\cos\left(\left(\frac{13\pi}{18}-\frac{2}{\pi}\left(\frac{13\pi}{18}-1\right)x\right)x\right)+l_{90}, \quad (4)$$

there $l_0=l\big|_{x=0^0}$ and $l_{90}=l\big|_{x=90^0}$ are real profile length, when abrasion direction is equal to 0 and 90 degrees, respectively.

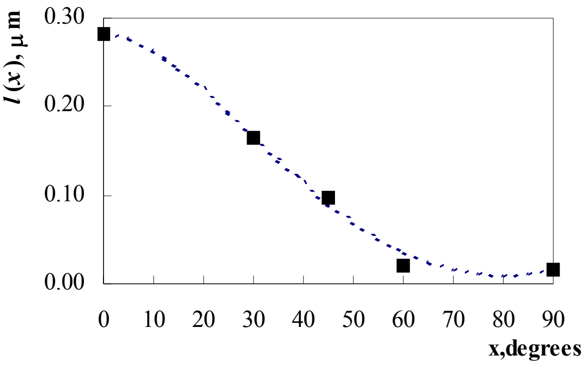

**Fig. 5.** The real profile length $\Delta l$ in dependence of abrasion treatment direction: --- – theoretical curve (Eq. 4), ■ - experimental points

The comparison of experimental and empirical results, calculated according to the Eq. 4 is presented in Fig. 5. The correlation coefficient for comparative data was 0.998.

The approximation results of shear lap tests in dependence on the substrate abrasion direction can be expressed according to the relation:

$$P(x)=\frac{P_{90}-P_0}{\sin\left(\frac{\pi^2}{16}\right)}\sin\left(\frac{\pi}{8}x\right)+P_0\ , \tag{5}$$

where $P_0 = P\big|_{x=0^0}$ and $P_{90} = P\big|_{x=90^0}$ are the shear strength of adhesive joints at abrasion direction of 0 and 90 degrees, respectively. The comparison of obtained experimental results and calculated according to the Eq. 5 are presented in Fig. 6.

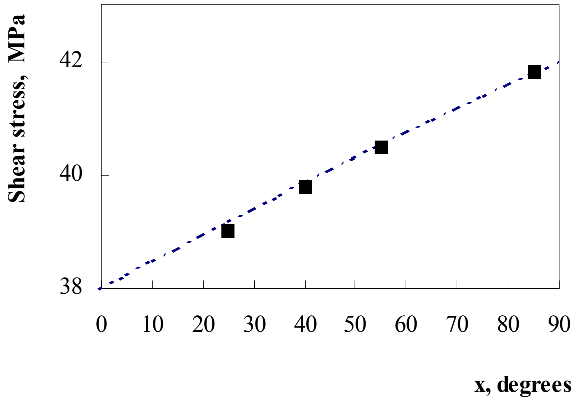

**Fig. 6.** Shear lap stress of adhesive joints in dependence on the substrate abrasion direction *x* (--- – theoretical curve according to the Eq. 5, ■ – experimental points)

One can see, that both experimental and theoretical results are in good agreement. It allows suggesting that the Eq. 5 is suitable for prediction of shear strength of adhesive joints in dependence of substrate abrasion direction.

## CONCLUSIONS

The effect of substrate surface abrasion direction with respect to the loading direction on the size of real surface area and adhesion properties has been investigated.

The statistical analysis of surface roughness parameters showed that correlation function of real profile length is independent on the surface abrasion direction. Only variation in function correlation coefficients was found.

The prediction of real surface length in dependence on the surface abrasion direction can be achieved when two marginal values of real profile length - perpendicular and along loading direction - are known. Empirically it relates on the second fluxion of correlation function $K(\tau)$, which describes real profile length of roughened substrate surface.

The effect of abrasion treatment direction on the adhesion strength of lap shear joints can be predicted empirically if shear strength in marginal points are known.

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