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ON THE POSSIBILITY OF DETERMINING THE MICROTOPOGRAPHIC CHARACTERISTICS OF THE AUTO SHEET SURFACE IN TECHNOLOGICAL PRODUCTION LINES

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Abstract. One of the important parameters for assessing the surface quality of a car sheet are parameters such as R_a and RP_c. These parameters describe the average value of the profile ordinate modulus and the average value of the number of peaks per unit length of the profile, but they do not provide complete information about the topographic structure of the rough surface. In this paper, as an alternative, we propose the use of complex parameters $\boldsymbol{R_{\Delta q}}$ of the RMS slope angle of micro faces of a rough surface and $\boldsymbol{\tau_e}$ – correlation distance of a rough surface profile.

$\mathbf{R_{\Delta q}}$ is a complex parameter. It simultaneously takes into account both the altitude and frequency parameters of the surface profile. Its values are more rigidly correlated with the coefficient of dry and viscous friction, with the strength characteristics of thin-layer materials, with the oil absorption capacity of the surface layer.

The parameter $\boldsymbol{\tau_e}$ is used for very smooth surfaces. It has a clear physical interpretation as the distance above which the correlation relationship between the surface ordinates is lost. This distinguishes it from the empirical parameter R_{Pc}

The paper describes the technique of measuring $\boldsymbol{R_{\Delta q}}$ and $\boldsymbol{\tau_e}$ by reflectometric method by scattered laser radiation indirectrices (SLRI) and software tools for analysing SLRI by comparing experimental and theoretical data. Examples of the use of this methodology and software tools for determining the surface parameter $\boldsymbol{R_{\Delta q}}$ of both cold-rolled and galvanised automotive sheet are given.

The results of this work can be used for the development and implementation of devices for non-contact measurement of the most important tribological surface characteristic $\boldsymbol{R_{\Delta q}}$in the technological lines of automotive sheet production.

***Keywords*:** roughness parameters, contact and non-contact methods of measuring roughness parameters, reflectometry, indicatrix, autosheet surface, software tools

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О ВОЗМОЖНОСТИ ОПРЕДЕЛЕНИЯ СРЕДНЕКВАДРАТИЧЕСКОГО УГЛА НАКЛОНА МИКРОГРАНЕЙ ШЕРОХОВАТОЙ ПОВЕРХНОСТИ В ТЕХНОЛОГИЧЕСКИХ ЛИНИЯХ ПРОИЗВОДСТВА АВТОЛИСТА

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Аннотация. Одними из важных показателей оценки качества поверхности автолиста являются такие параметры, как R_a и RP_c. Эти параметры описывают среднее значение модуля ординат профиля и среднее значение числа пиков на единицу длины профиля, но они не дают полной информации о топографической структуре шероховатой поверхности. В данной работе в качестве альтернативы предлагается использование комплексных параметров $\boldsymbol{R_{\Delta q}}$ среднеквадратического угла наклона микрограней шероховатой поверхности и $\boldsymbol{\tau_e}$ – корреляционного расстояния профиля шероховатой поверхности.

R_Δq – это комплексный параметр, учитывающий как высотные, так и частотные параметры профиля поверхности одновременно. Его значения более жёстко корреляционно связаны с коэффициентом сухого и вязкого трения, с прочностными характеристиками тонкослойных материалов, с маслоёмкостью поверхностного слоя.

Параметр τ_e используется для очень гладких поверхностей. Он имеет чёткое физическое толкование как расстояние, выше которого корреляционная связь между ординатами поверхности теряется. Это его отличает от эмпирического параметра $\boldsymbol{P_c}$.

В статье описана методика измерения $R_{\Delta q}$ и τ_e рефлектометрическим способом по индикатрисам рассеянного лазерного излучения (ИРЛИ) и программные средства для анализа ИРЛИ путём сопоставления экспериментальных и теоретических данных. Приведены примеры использования данной методики и программных средств для определения параметра $R_{\Delta q}$ поверхности как холоднокатаного, так и оцинкованного автолиста.

Результаты работы данной можно использовать для разработки и внедрения приборов для бесконтактного измерения важнейшей трибологической характеристики поверхности $R_{\Delta q}$ в технологических линиях производства автолиста.

Ключевые слова: параметры шероховатости, контактные и бесконтактные способы измерения параметров шероховатости, рефлектометрия, индикатриса, поверхность автолист, программные средства

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1. Research problem statement

More than forty surface performance characteristics depend on surface microtopography [1–8]. These are electrical contact [9, 10], adhesion contact [11–13], thermal contact [14], and surface contamination [15]. Since more than ten articles are annually published on the friction and wear coefficient dependences on surface microtopography, it is reasonable to point out the monographs in which a large bibliographic review on this topic is made [16–23].

The list of works on the elastic-plastic contact study of rough surfaces is equally extensive [24–31].

Of these works, it is necessary to single out the works of applied character, devoted to manufacturing the products with the given surface microtopography. Surface microtopography according to modern standards has a wide set of digital and functional surface characteristics. Some of them are regulated as a quality parameter of products. For example, in order to ensure better stampability of the automotive sheet, better adhesion bonding of the coating with the substrate and better marketability of car parts and bodies, the automotive sheet with strictly regulated and controlled parameters of surface microtopography is required.

Most often the amplitude parameter of rough surface – $\boldsymbol{R_a}$ and $\boldsymbol{R_q}$ is regulated – arithmetic mean and mean square value of surface ordinates. The frequency parameter of the rough surface $\boldsymbol{P_c}$ is less frequently regulated – the number of surface peaks per 1 cm of the profile above the c level [32–38]. In order to produce products with these regulated parameters it is necessary to have instruments that fix these parameters in the technological production line. Such non-contact instruments have been created and are used, for example, for the production of automotive sheet.

But there are other surface microtopography parameters, which more rigidly determine the operational characteristics of the surface [39–41], but their measurement in the flow is difficult.

For example, the mean square angle $\boldsymbol{R_{\Delta q}}$ of micro faces inclination of a rough surface. This is a complex parameter that simultaneously takes into account both height and frequency parameters of the surface profile and its values are more rigidly correlated with the coefficient of dry and viscous friction, with the strength characteristics of thin-layer materials, with the oil capacity of the surface layer.

Note also that, in contrast to the empirical parameter $\boldsymbol{P_c}$, the spatial intervals of a rough surface are more precisely defined by the correlation interval $\boldsymbol{\tau_e}$. It has a clear physical interpretation as the distance between ordinates, above which the correlation relation between surface ordinates is lost.

In this paper, it is shown that these parameters can be determined in a non-contact reflectometric way using specific software for processing the vector of the angular distribution values of the reflected radiation intensity.

According to P. Bouguer, all information about the surface microtopography is contained in the indirectrix of scattered monochromatic radiation. The theory of radiation scattering from surfaces with different topography and microtopography has been sufficiently developed, although some problems have not been completely solved [42–51]. Various optical non-contact methods for determining many parameters of surface microtopography have been developed, the principles of which are outlined in the monograph [52]. Also, various methods of computer modelling are currently used to solve such problems [53–54].

This study considers the possibility of non-contact measurement of parameters $R_{\Delta q}$ and τ_e in the technological flow of production of products. If such devices are available, it is possible to produce products with regulated microparameters $R_{\Delta q}$ and τ_e.

2. Working physical laws

Let $\boldsymbol{\lambda}$ be the wavelength of light incident on the surface by a collimated flux. Let $\boldsymbol{\tau_e}$ – correlation interval characterising the degree of ruggedness of the surface profile, but **Rq** – mean square height of surface irregularities.

In reflectometry, a surface that satisfies the following inequality

$$\boldsymbol{\tau_e} \gg \boldsymbol{\lambda} \gg \mathbf{Rq} \quad (1)$$

is often called a smooth surface. Surfaces with violated inequalities (1) are called rough surfaces.

The scattering indikatrix from a smooth surface I is in its physical essence a Fourier image of this surface and therefore is determined by the spectral power function – PSD by the following formulae [47–51]:

$$I(\theta_i, \boldsymbol{\tau_e}) = C \cdot \pi \cdot k^4 \cdot [1 + cos(\theta_o) \cdot cos(\theta_i) - sin(\theta_o) \cdot sin(\theta_i)]^2 \cdot PSD(\theta_i, \boldsymbol{\tau_e}), \quad (2)$$

where

$k = 2 \cdot \pi / \boldsymbol{\lambda}$;

$$PSD(\theta_i, \boldsymbol{\tau_e}) = \frac{4 \cdot \boldsymbol{\tau_e}}{1 + \left[k \cdot \boldsymbol{\tau_e} \cdot \left(sin(\theta_o) - sin(\theta_i)\right)\right]^2};$$

θ_o – laser incidence angle;

θ_i – scanning angle;

τ_e – mean value of the correlation interval;

C – coefficient depending on the Fresnel reflection coefficient and hardware function.

Dependences $I(\theta_i, \boldsymbol{\tau_e})$ at fixed values are shown in Fig. 1.

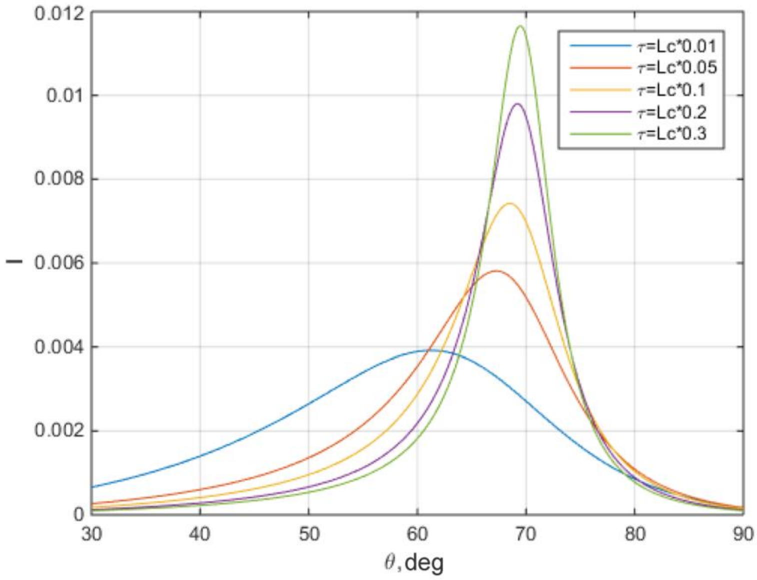


Fig. 1. Indicatrices of a smooth surface with different values τ_e. Here $\theta_o = 70^o$

The rough surface indikatrix is determined by the laws of geometrical optics and is therefore determined by the distribution function of the tangent angles of the inclination angles of the micro faces of the rough surface PSF by the following formulae [47–51]:

$$I(\theta_i,\boldsymbol{tg}) = C\cdot\frac{{k_1}^2\cdot cos^2(\theta_i)}{\pi}\cdot f^2\cdot PDF(\theta_i,tg); \quad (3)$$

where

$$f \equiv f(\theta_i) = \frac{1+cos(\theta_o)\cdot cos(\theta_i) - sin(\theta_o)\cdot sin(\theta_i)}{cos(\theta_i)\cdot\left(cos(\theta_o)+cos(\theta_i)\right)};$$

$$k = 2\cdot\pi/\boldsymbol{\lambda};$$

$$v_z = k\cdot\left(cos(\theta_o)+cos(\theta_i)\right);$$

$$v = k\cdot\left(sin(\theta_o)-sin(\theta_i)\right);$$

$$PDF(\theta_i,tg) = \pi\left(\frac{1}{2\cdot v_z\cdot\boldsymbol{tg}}\right)^2 exp\left(-\left(\frac{v}{v_z\cdot\boldsymbol{tg}}\right)^2\right),$$

where $\boldsymbol{tg}$ is the average value of the inclination angle tangent of the surface profile micro-facets. The designation of other quantities is similar to the formula designations (2).

Dependences $I(\theta_i,\boldsymbol{tg})$ at fixed values are shown in Fig. 2.

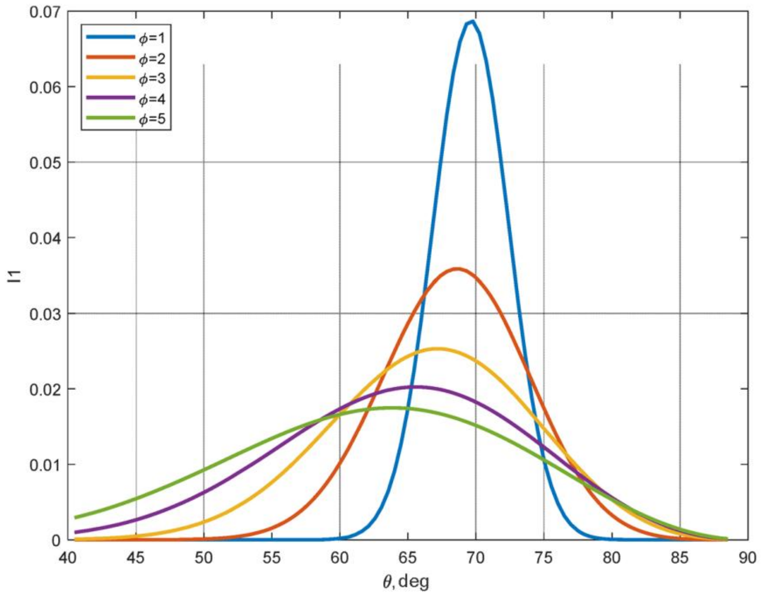


Fig. 2. Rough surface indicatrices with different values of inclination angles of micro faces of a rough surface ψ. Here $\theta_o = 70^o$

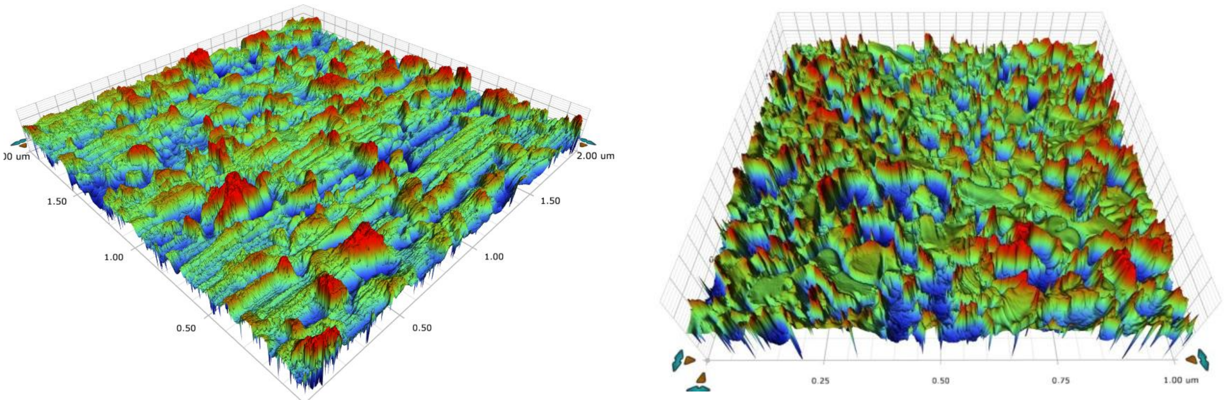
3. Experiment description

The research was carried out on samples of automotive sheet. Stampability of automotive sheet depends on the amplitude parameter $\boldsymbol{R_a}$ and on the step parameter $\boldsymbol{\tau_e}$. But the greatest correlation dependence of stampability is observed with the hybrid parameter – $\boldsymbol{R_{\Delta q}}$.

Surface maps were determined on the Contour GT K1 optical profilometer (Fig. 3).

The MarSurf PS1 instrument was used for determination of surface microtopography parameters by stylus method. The digital output from this device allowed determining the vector of surface profile values and with the help of special software it is possible to determine the parameters $\boldsymbol{R_{\Delta q}}$ and $\boldsymbol{\tau_e}$ with powerful enough averaging [53]. The parameters $\boldsymbol{R_{\Delta q}}$ and $\boldsymbol{\tau_e}$ were calculated strictly according to the standards of GOST R ISO 4287-2014 and ASME B46.1-2019.

Experimental determination of scattered radiation indicatrices was carried out on the AKIIRI (Automated Complex for Measurement of Scattered Radiation Indicatrices) installation of the Research Centre ‘Microtopography’ of Nosov Magnitogorsk State Technical University. AKIIRI is based on the X-ray precision goniometer (GUR-5). The spectrum of the registered radiation of the unit is set by the radiation source – helium-neon laser (LG-78) with λ = 0.62 μm and photosensors (FD-24K). The plane of incidence and reception of radiation was always perpendicular to small surface risks (i.e., to the direction of auto sheet training).



a) b)

Fig. 3. A surface map example of a automotive sheet before galvanizing (a) and after galvanizing (b)

The software was calibrated according to the readings of the stylus device and the results of reflectometric measurements with the software, which will be discussed below.

But before this issue is considered, it is necessary to make an important remark. If we are talking about a roughness profile (or a rough surface), it should be remembered that this implies that two operations have been performed on the ordinates of the measured profile (or surface), according to the above mentioned standards:

1) filtering by a high-pass filter with parameter λ_3;

2) filtering by a low-pass filter with parameter λ_c.

These are the usual operations of vector convolution of profile ordinate values with the weighting coefficients of the narrow Gaussian window and with the coefficients of the wide Gaussian window with appropriate parameters, when the high-frequency component and the low-frequency component of the profile (or surface) are eliminated. In this paper, standard Gaussian filters with parameters $\lambda_3 = 0.5$ μm and $\lambda_c = 800$ μm. Using any roughness parameters without specifying these filter parameters lacks sense.

Since the standards for the texture of the automotive sheet strictly specify this type of filtering, it is obvious that such a surface, when using this laser radiation, should be considered rough.

4. Description of the experiment software tools

The programme works as follows (Fig. 4). The measured indicatrix is normalised to one (if necessary, it is processed by various filters to eliminate outliers). Then the graphs of theoretical indicatrix models for rough surface and for slightly rough surface are superimposed on it. The condition of adequacy of theoretical indicatrices to the experimental indicatrix is estimated by the sum of modules of ordinate differences between the two curves.

The calibration algorithm of the reflectometric unit by the reference sample before measurements of the parameters $\boldsymbol{R_{\Delta q}}$ or $\boldsymbol{\tau_e}$, is shown in Fig. 4.

After calibration the conversion coefficients are stored in block 1.1.

The algorithm of processing IRLI of prototypes is carried out according to a similar algorithm, but it excludes blocks 2.1, 2.2, 1.4 and 2.4.

Fitting of the theoretical indicatrix to the experimental one is carried out by two fitting parameters: by values $\boldsymbol{R_{\Delta q}}$ or by values $\boldsymbol{\tau_e}$ (for a smooth surface) and by the shift of the indicatrix along the abscissa axis ‘delta’ – the angles of radiation reception.

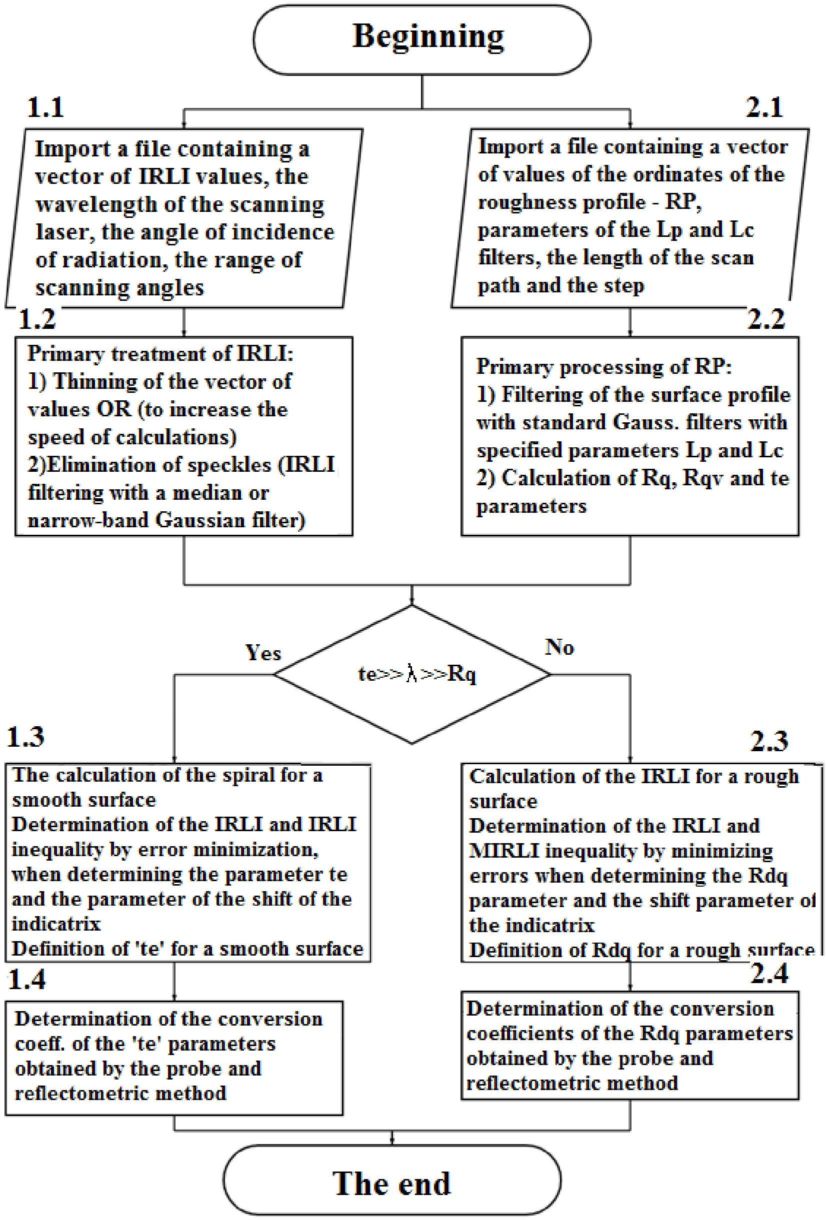


Fig. 4. Algorithm for processing the calibration and measurement results $R_{\Delta q}$ or τ_e

For the evaluation of the situation, model representations of MIRLEY indicatrices are used (see the left part of Fig. 5 and 6).

The exact determination of the parameters is carried out by the three-dimensional dependence of the estimation error with the arguments $\boldsymbol{R_{\Delta q}}$ or $\boldsymbol{\tau_e}$ and the shift parameter ‘delta’ (see the centre part of Fig. 5 and 6).

The results with the lowest error are presented in the form of two plots: IRLI and MIRLI, the closest to it (see the right part of Fig. 5 and 6).

The final results of such software processing are:

1) parameters $\boldsymbol{R_{\Delta q}}$ or $\boldsymbol{\tau_e}$;

2) an adequacy assessment of the given used theoretical model.

The case of IRLI processing of a rough surface is shown in Fig. 5.

The case of IRLI processing of a smooth surface is shown in Fig. 6.

Rough surface model at θ_o with different tg

Error matrix. The X-axis is a search of the indicatrix according to the tg parameter. The X-axis is a displacement of the indicatrix along the axis of the abscissa

Comparison of the theoretical and experimental indicatrix reflected from a rough surface at θ_o = 70°

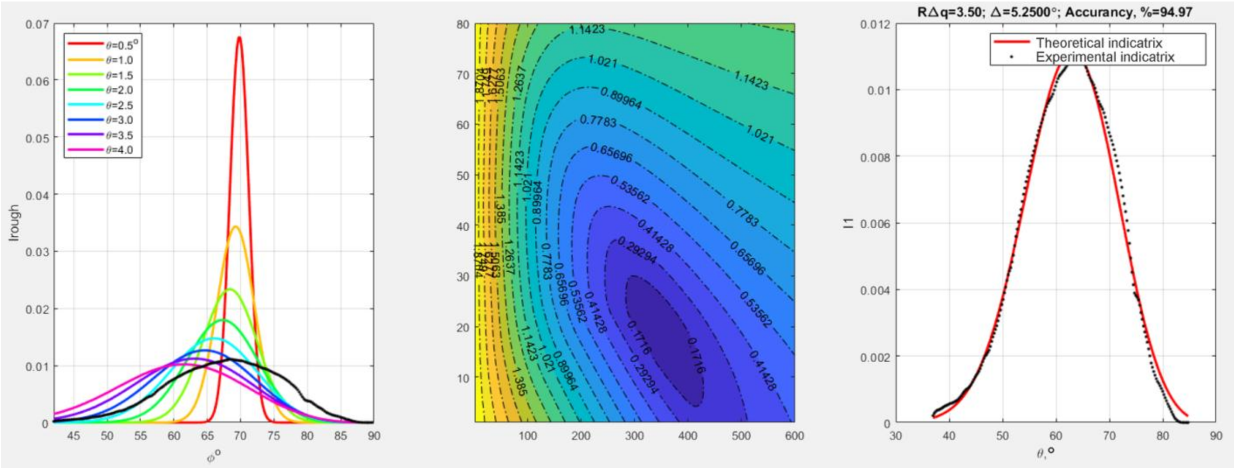


Fig. 5. Block programme for determining $R_{\Delta q}$

Smooth surface model at θ_o with different τ_e

Error matrix. The X-axis is a search of the indicatrix according to the τ_e. parameter. The X-axis is a displacement of the indicatrix along the axis of the abscissa

Comparison of the theoretical and experimental indicatrix reflected from a smooth surface at θ_o = 70°

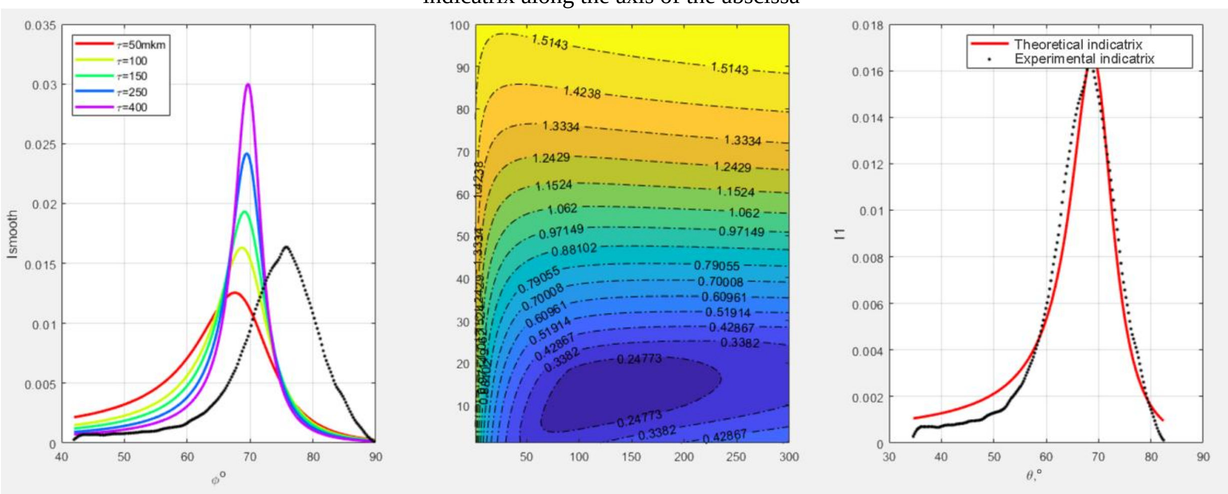


Fig. 6. Block programme for determining τ_e

5. Results of the research

The dependence between the average angle inclination determination of profile micro facets defined by reflectometric and stylus method was checked. This dependence for a large batch of auto sheet samples is shown in Fig. 7, 8. A good correlation dependence between the inclination angles of surface profile micro-facets determined by reflectometric and stylus method is obvious.

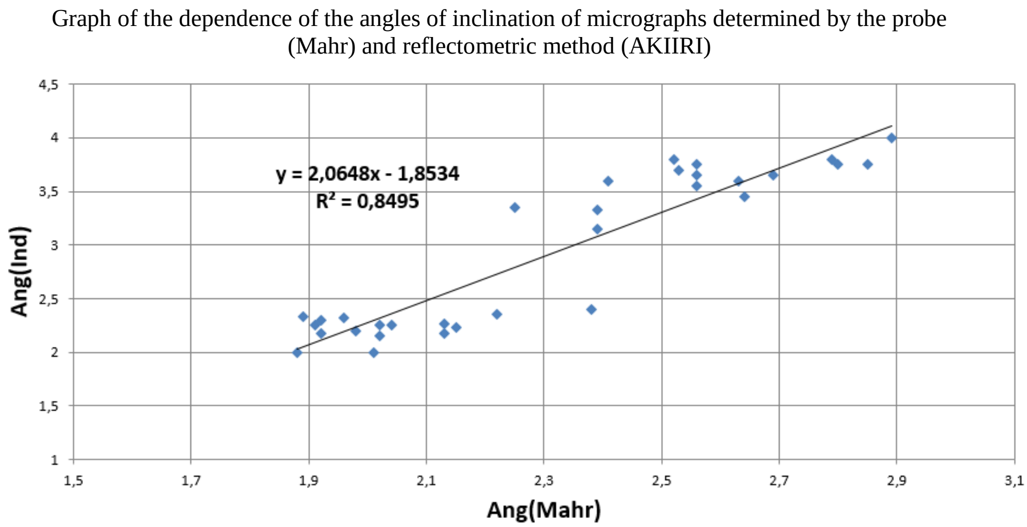


Fig. 7. About correlation relation of inclination angles of profile micro facets determined by stylus and reflectometric method of automotive sheet before galvanizing

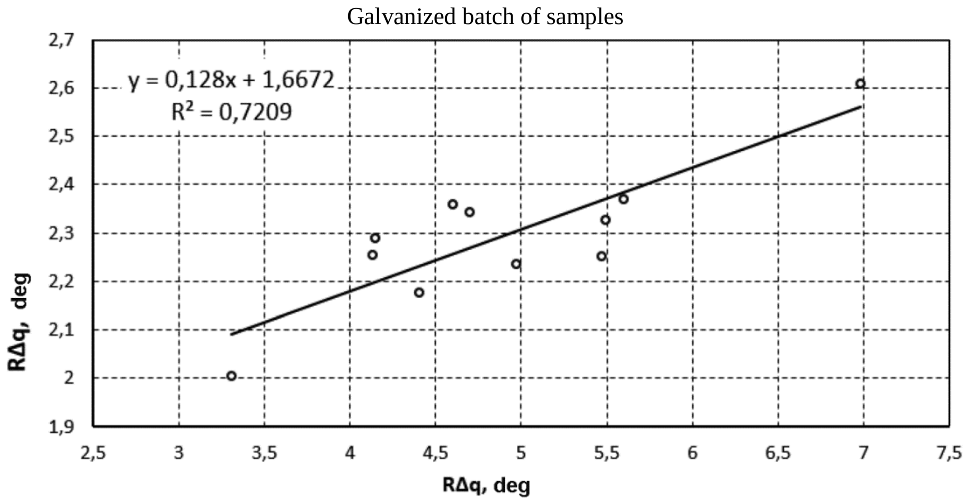


Fig. 8. Correlation between the inclination angles of profile micro-facets determined by stylus and reflectometric methods for galvanised automotive sheet

The classical relationship between the amplitude parameter $\boldsymbol{R_a}$ and the maximum IRLI value was also verified for galvanised auto sheet (Fig. 9a) and cold rolled auto sheet (Fig. 9b).

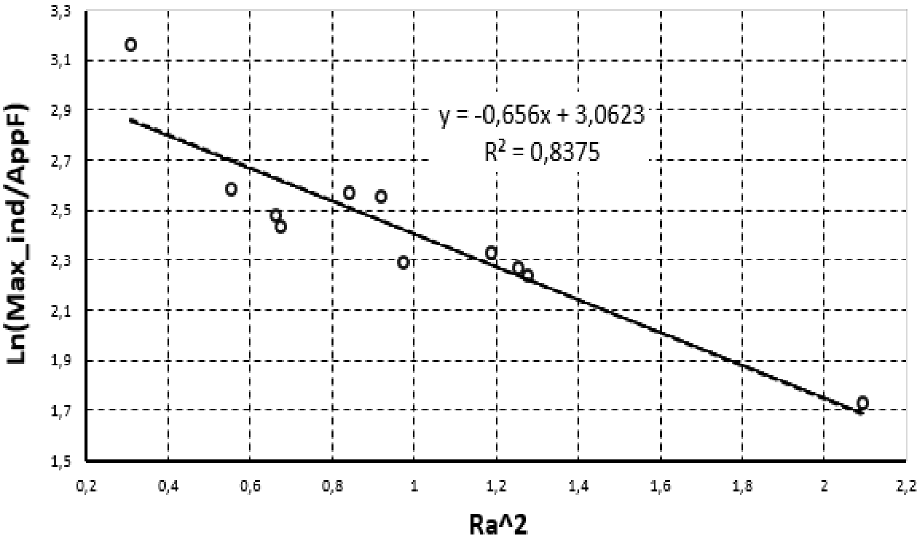
Each point in the graphs of Fig. 7–9 is the average of 9 experimental values of one sample determined by both stylus and OTDR methods.

Conclusions

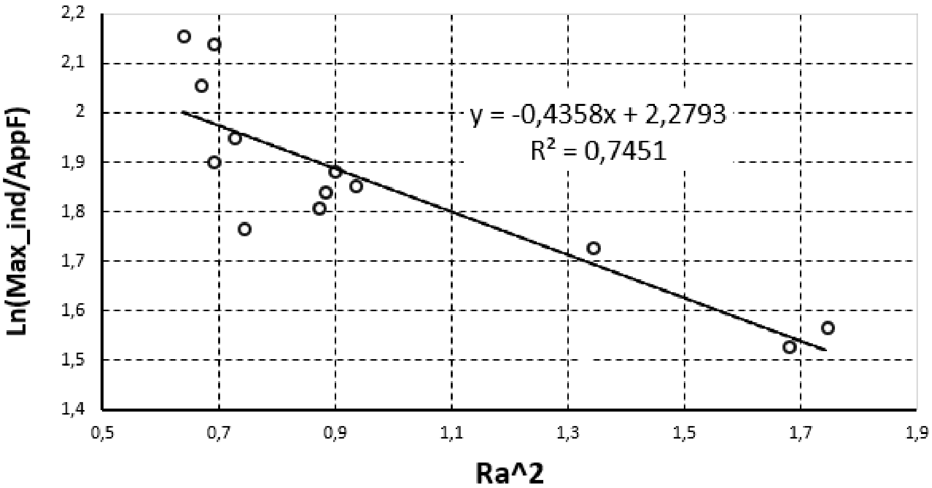
The possibility of measuring the parameter $R_{\Delta q}$ (mean square angle of inclination of micro faces of a rough surface) of a rough surface by non-contact reflectometric method is shown. It is confirmed by experimental data for dressed and galvanised automotive sheet. This method of determination $R_{\Delta q}$ can be realised directly in technological lines of autosheet production.

The possibility of measuring the parameter $\boldsymbol{\tau_e}$ (correlation interval) of a smooth rough surface by non-contact reflectometric method is also shown.

This non-contact method of measurement $R_{\Delta q}$ and $\tau_e$can be used in the study of the dependence of the surface performance characteristics on the surface microtopography, which are specified in Section 1 of this article.



a)



b)

Fig. 9. Dependence of the maximum IRLI value on the roughness parameter R_a:
a) galvanised automotive sheet; b) cold-rolled automotive sheet

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