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LASER SCATTEROMETRY FOR DETECTION OF SQUAT DEFECTS IN RAILWAY RAILS

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Abstract: *The paper concerns a defectoscopy of squats occurring on the surface of the rail head. Disadvantages of traditional methods being used in detection of such defects were also presented. Authors proposed a new method based on simplified laser scatterometry to detect these defects. Physical model of the laser beam scattering by edges of such defects and simulation results were given. An experimental set-up for practical testing of this method was designed and constructed. This system enabled measurements of squat defects occurring in the section of the rail extracted from the track. The analysis of obtained results was performed. Authors also indicated directions of further research and development.*

Key words: *railway rails, squat defects, laser scatterometry.*

1. Introduction

Surface defects occurring on the rail head are extremely difficult to detect, thus they can pose a serious threat to the railway traffic. Rolling contact fatigue defects such as head checking, shelling and squat in particular deserve an attention. All of them are dangerous and can lead to break of rails what in turn can cause the train derailment. They are located beneath the surface of the rail head at a distance ranging from a fraction of millimeter to several millimeters. Effective detection of them is a crucial issue and has a significant impact on the safety and comfort of the journey (Jeong, 2003). Surface defects are numerously represented by squats. Issues concerning the development and detection of rolling contact fatigue defects are intensively investigated by European research community. Delft University of Technology is one of leading centre which conducts research of this type (Tay et al., 2003). Additionally, these issues were also presented in INNOTRACK research report (INNOTRACK project report, 2009).

Until now, PKP PLK SA and other railway lines headquarters have used methods, which often fail to detect such defects. The most popular ultrasonic method requires perfect acoustic contact what in turn cannot be satisfied in case of squats occurring in the shape of large and deep cracks located in the central part of the rail head. Method based on eddy currents (belonging to the magnetic methods) also requires to keep a constant distance between the sensor and the surface of the rail. It is infeasible in real conditions occurring on the track (Hansen and Calvert, 2002). The newest Magnetic Metal Memory method is under analysis and test and its usefulness has not been settled yet.

Application of visual method (based on image processing and analysis) for detection of surface defects gave good results (Bojarczak, 2013), however it has not yet been applied by PKP PLK SA. For the time being, the diagnosis of rails is realized only with the use of the ultrasonic method (Lesiak, 2008). However this technique is ineffective for surface defects and allows for detection mostly of defects occurring under the surface of the rail head. More than 60% of surface defects remain undetected by ultrasonic method (Bojarczak, 2013).

Authors proposed a method based on simplified laser scatterometry for detection of squats. In Poland, these defects during 2012 and 2011 years caused 488 and 340 breaks of rails, respectively. It constitutes 19% of all breaks occurring on tracks (Bojarczak, 2013). These defects could be prevented by grinding (Kumar, 2006). However they require detection in early stage of their development. It was a strong motivation for authors to deal with this problem. The paper presents the physical model of laser beam scattering by edges of squats and simulation results. The laboratory set-up was also presented. Extracted from the track, sections of rails with squats of different shapes and depths were investigated, fig. 1a. The analysis of obtained measuring results was also performed. Areas of further research leading to an application of this method were also given.

An application of laser scatterometry in detection of surface defects is a new and innovative approach recently proposed by authors in (Lesiak, 2010; Lesiak and Bojarczak, 2010; Lesiak and Wlazło 2013).

2. Squats – their characteristics

Squats belong to rolling contact fatigue defects. They appear as a result of interaction of wheels with the running surface of the rail (Kapoor et al., 2006; Zhao, 2012).

Each squat consists of two main subsurface cracks: a leading one that propagates in the direction of train travel, and a trailing one that propagates in the transversal direction. The leading crack is usually several times longer than the trailing crack and contains one main crack with a number of secondary or minor cracks branching off this crack (Engineering Manual Track, 2013). Squats are surface or near-surface initiated defects, which can be of two types:

- The more common type of squats, which are initiated on the crown or ball of the rail head (Rail Defects Handbook, 2006). They are easily identified visually, since they appear as dark spots or “bruises” on the running surface of the rail. The defective area seems be Darkened due to the subsurface cracking which, occurs typically on a horizontal plane, approximately 3-5 mm below the rail surface, and which causes a depression on the rail surface.
- Squats that are initiated from the gauge corner checking cracks. They grow laterally and spread towards the crown of the rail head, and in their advanced stages appear very similar to the rail crown squats (Rail Defects Handbook, 2006).

Subsurface cracks, as illustrated in fig. 1, can often lead to spalls of surface. Although these flaws are usually removed from the track on time (Railtrack PLC Guidelines, 2001), they sometimes can cause breaks of rails, fig. 1d.

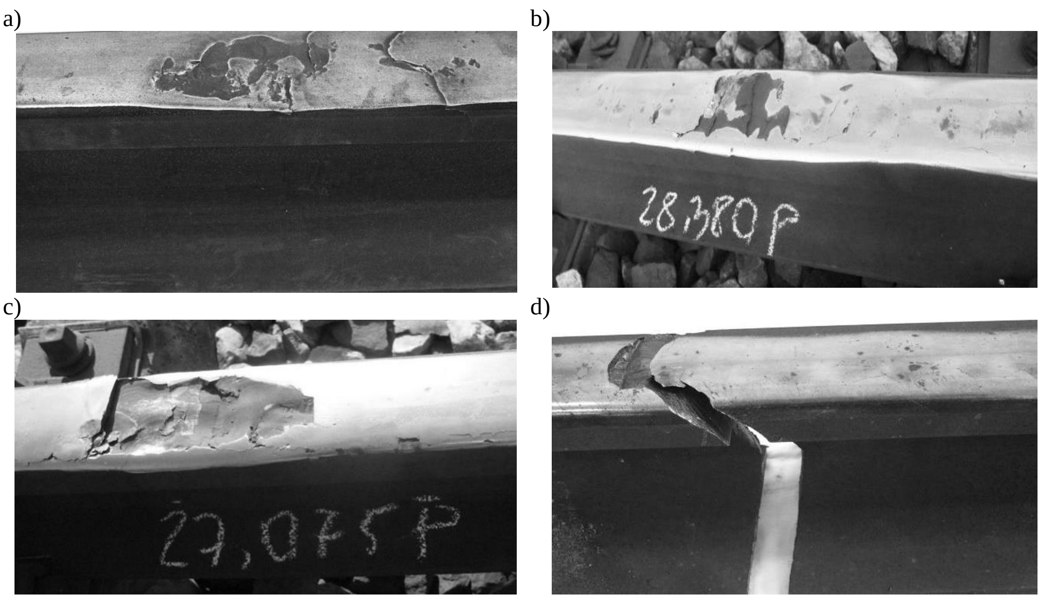


Fig. 1. Examples of squats: a) a flaw examined in laboratory, b) and c) flaws occurring on the track, d) a break of the rail caused by squat

3. The model of the light scattering phenomena

Light scattering, and its behavior during passing through different edges and surfaces is a phenomenon that requires thorough physical analysis (Kapłonek, Łukianowicz, and Nadolny, 2012; Łukianowicz, 2007; Moreno-Báez, et al., 2011). Scalar model uses diffraction theory formulated by Fresnel-Kirchhoff to describe the light scattering phenomena on rough surfaces, typical for shallow surface defects. This model, utilizing the methods of wave optics, was presented by the coauthors in (Lesiak and Wlazło, 2013).

In this paper, authors applied the geometrical optics in order to describe the phenomena of the light scattering by the deep squat-type defects of big size. In this approach based on simplified variant of laser scatterometry, a single photo-detector (photo-diode) receives the light reflected by the surface of the defect. The light is picked from a narrow angle θ_2 – see fig. 2.

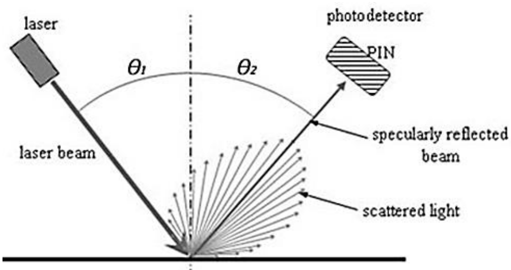


Fig. 2. Layout of the laser and the PIN photo-detector in laboratory set-up

A monochromatic light was used in our experiments with laser scatterometry. In the frame of geometrical optics, laser light is represented by the set of narrow beams (rays) (Lesiak, 2010). The fact that the length of the light wave is much shorter than dimensions of typical defects under analysis, was the main premise for authors to use the model based on geometrical optics.

The approach discussed is entirely different to that utilized in (Kapłonek, Łukianowicz, and Nadolny, 2012; Łukianowicz, 2007, Nadolny and Kapłonek, 2010), where authors observed and analyzed the diffraction effects of laser light scattered by surface with micrometer-sized roughness. The method of measurements and developed geometrical model are 1D-type but depth-sensitive in contrary to the typical 2D but "flat" techniques of image collection and processing (Lesiak and Wlazło, 2014).

The authors analyzed behavior of laser beam passing through the artificial patterns of defects. These patterns were carved on the surface of rail head. They are in the form of transverse lines with different lengths x and depths h (fig. 6).

In real conditions, reflections can be described as a superposition of specular reflections and light scattering on the surface. For specular reflections, the whole beam is reflected from the surface in one direction. This phenomenon takes place for perfectly smoothed surfaces whereas light scattering (in all directions) occurs for perfectly roughed surfaces (Lambert model of the surface) (Lesiak and Wlazło, 2013; Moreno-Báez, et al., 2011; Tay et al., 2003). Authors performed the measurements of the distribution of light scattered by the different regions of defects' surface.

Theoretical model assumes that geometrical optics can describe sufficiently well a reflection of laser beam from the surface. In this case, wave effects (diffraction and interference) can be neglected. Laser beam is regarded as a set of independent light rays reflected from the surface according to the law of specular reflection. Potential diffusional light scattering can be taken into account by an introduction of the function defined for the given surface. However such approach requires a further research.

Fig. 3 shows the example of the reflection of laser beam from the defect of rectangular profile and edges with steps. The constant distance between the laser and the detector is assumed. The beam, when falls on first stair of the edge of the rectangular defect (fig. 3a), splits into two parallel beams. One of them is reflected from the surface of the rail head, and the second one - from the bottom of the defect. The angles of both reflections are the same, however a parallel shift of beams appears and it is proportional to the depth of the flaw. In consequence only part of the beam reaches the window of photo-detector which moves together with the laser. It causes a noticeable decrease in light intensity received by the detector. The whole beam is parallelly shifted (fig. 3b) when reflects from the central part of the bottom of the defect. However, when the beam reflects from the latter step of the edge of the defect, it is partially or entirely shielded by its wall (fig. 3c). The beam reflected from the first edge of two-steps artificial defect splits into three parallel shifted beams (fig. 3d).

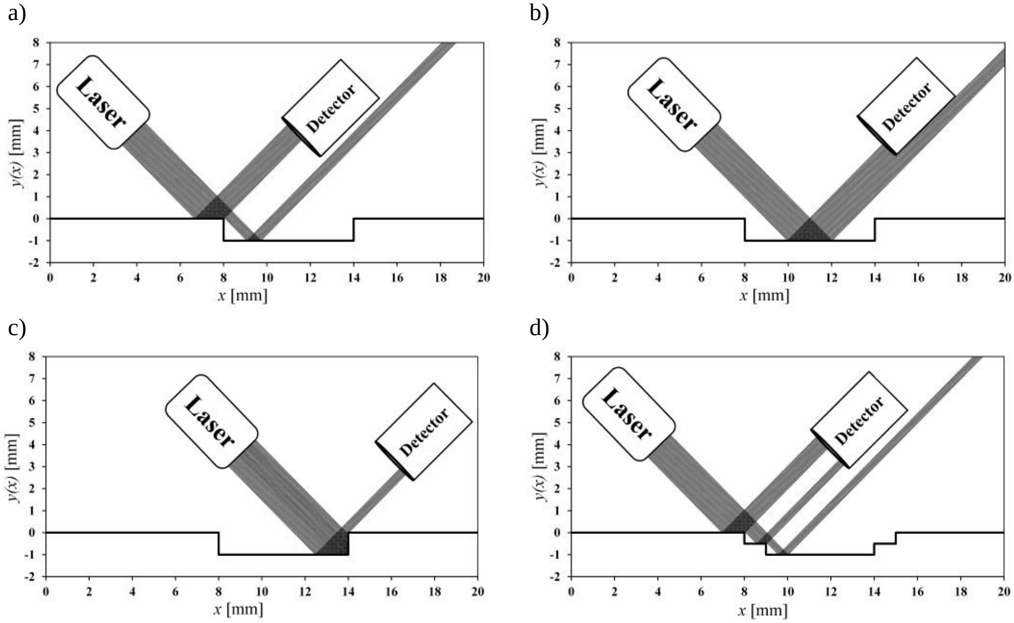


Fig. 3. Illustration of the laser beam reflections from the edges of the model defect of the rectangular profile: a) near the front edge of the of defect, b) from the bottom of the defect, c) near the back edge of the defect. Case d) presents a light reflection from the front defect edge of the two step-like profile

The intensity of the light beam that reached the detector after reflection from the flat horizontal surface of the bottom of the defect is strictly correlated with parallel shift of the laser beam and depends on geometrical parameters of measuring system. Theoretical estimation of the intensity of the detected light is given by the following formula in the frame of geometrical optics approach:

$$I = \begin{cases} kI_0 & \text{for} \quad h \le \frac{d_d - d_s}{4\cos\alpha} \\ kI_0 \frac{d_d + d_s - 4h\cos\alpha}{2d_s} & \text{for} \quad \frac{d_d - d_s}{4\cos\alpha} \le h \le \frac{d_d + d_s}{4\cos\alpha} \\ 0 & \text{for} \quad h \ge \frac{d_d + d_s}{4\cos\alpha} \end{cases} \quad (1)$$

where:

I_0 – denotes the light intensity after reflection from the flat horizontal running surface of the rail,

k – denotes the rate of a reflection coefficient for light reflected from the flat surface of the defect to a reflection coefficient for light reflected from the flat running surface of the rail,

I – denotes light intensity received by the detector with the window of predefined diameter,

d_d – denotes diameter of the detector window,

d_s – denotes diameter of laser beam (at the assumption that $d_d > d_s$),

α – denotes the angle of laser beam incidence (equal to the angle of reflection) measured towards the rail plane ($\alpha = 90° - \theta$, fig. 2),

h – denotes the depth of defect model for rails with the edges of rectangular profile.

Changes in light intensity is caused by parallel shift of reflected laser beam what in turn results from the fact that the bottom surface of the defect is beneath the level of rail surface. In consequence only the part of the laser beam reaches the detector window.

In order to illustrate the relationship (1), exemplary values of parameters: d_d = 2 mm, d_s = 0.5 mm, k = 1, were chosen. Consequently, this relationship can be rewritten as:

$$\frac{I}{I_0} = \begin{cases} 1 & \text{for} \quad h \le \frac{0.375}{\cos\alpha}\,\text{mm} \\ 2.5 - \frac{4h}{\text{mm}}\cos\alpha & \text{for} \quad \frac{0.375}{\cos\alpha}\,\text{mm} \le h \le \frac{0.625}{\cos\alpha}\,\text{mm} \\ 0 & \text{for} \quad h \ge \frac{0.625}{\cos\alpha}\,\text{mm} \end{cases} \quad (2)$$

Fig. 4 illustrates the impact of parameters α and h on changes in laser beam intensity (registered by the detector) which were predicted with formula (2).

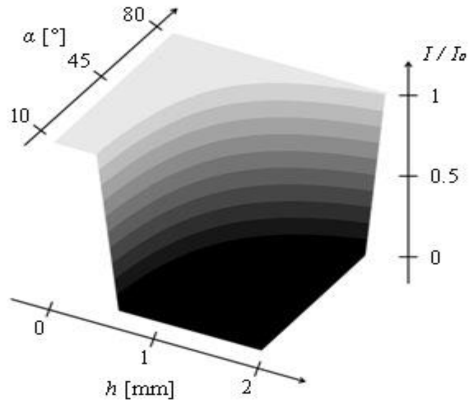


Fig. 4. Graph of the relative changes in laser beam light intensity I/I0 recorded by the detector after reflection from the bottom of the defect (away from the edges) theoretically predicted by the relationship (2) as a function of the defects depth h and the angle of laser beam incidence α

In the last stage of simulation, the relationship between changes in light intensity and the position of reflected beam was determined. In order to define this relationship, it is necessary to take into account three aspects of the phenomena under analysis:

1. During scanning the front edge of the flaw, the change in light intensity from I_0 to I is observed on the distance $dx_1 = \frac{d_s}{\sin\alpha}$.
2. A decrease in light intensity from I to 0 is registered on the distance $dx_2 = 2h\text{ctg}\,\alpha$, when the laser beam approaches latter edge of the defect. Additionally, if the laser beam is sufficiently narrow, the intensity of recorded light remains at zero level on the next section, $(dx_2 - dx_1)$ in length.
3. Then, an increase of light intensity from 0 to I_0 occurs on the distance $dx_3 = \frac{d_s}{\sin\alpha}$, when the laser beam leaves the region of defect.

Taking into account items 1-3 and formula (2), the relationship between changes in the intensity of reflected light $I(x)$ and the position x of laser point of incidence was found for the following values of parameters: α = 45°, h = 0.75 mm, d_s = 0.5 mm, d_d = 2 mm, k = 1. Moreover, the same values of reflection coefficients for light reflected both from running surface of the rail and from the surface of the defect were assumed. Fig. 5a and fig. 5b show the intensity ratio $I(x)/I_0$ of light registered by the detector after reflection by the defects and the defect profile $y(x)$ of the rectangular shape, respectively.

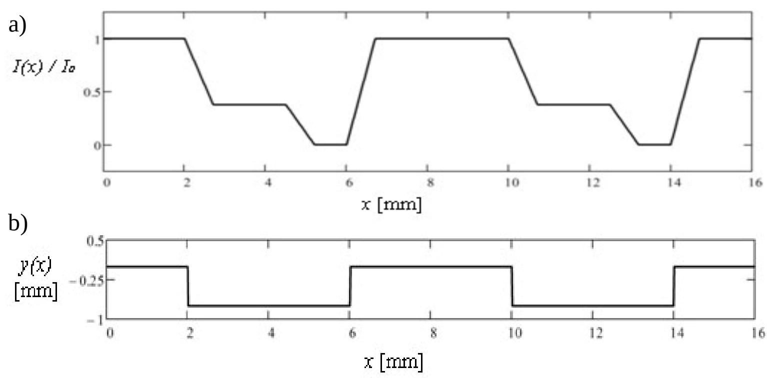


Fig. 5. The theoretical plot a) of the intensity ratio $I(x)/I_0$ of light registered by the detector after reflection by the defects b) of a rectangular profile $y(x)$. Predictions have been performed for the following set of parameters: α = 45°, h = 0.75 mm, d_s = 0.5 mm, d_d = 2 mm, k = 1

4. Description of Laboratory set-up

In the experiment, the fragment of the actual railway rail with artificial surface defects was used (fig. 6, fig. 9a).

Experiments (fig. 7) were carried out in the Laboratory of Diagnostic Systems at the Faculty of Transport and Electrical Engineering, University of Technology and Humanities in Radom.

In this experiment, as a light source (transmitter), the laser generating the red light beam of wave, λ=635 nm in length, and power of 20mW (ADL 63201TL) was used. The receiver of light beam reflected from the running surface of the rail is a photodiode PIN (*Positive - Intrinsic - Negative Photodiode*) with the radiant sensitive area in the shape of a rectangle with the side of 2.5mm. Transmitter-receiver pair constitutes rail scanning platform, which moves along the rail *X* with the step of 10 µm. The platform is driven by the stepper motor fitted with a worm gear. The displacement sensor which determines the current position of transmitter-receiver pair on the rail is realized by linear potentiometer connected to the voltage supplier and scaled in units of length.

The signal from the receiver is measured by the multimeter. The whole measuring system is controlled by the program "Laser" running on the computer. This program was written in VEE Pro development software (Angus and Hulbert, 2005). The system consists of measuring devices manufactured by Agilent, which communicate with the computer through GPIB interface (General Purpose Interface Bus), fig. 7.

Fig. 8 presents the exemplary results for defect of rectangular profile measured in VEE environment.

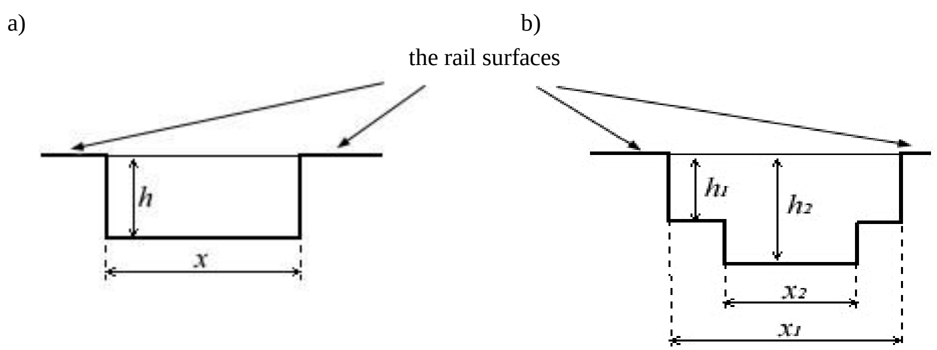


Fig.6. The model of surface defect: a) one step-like edge, b) two steps - like edge

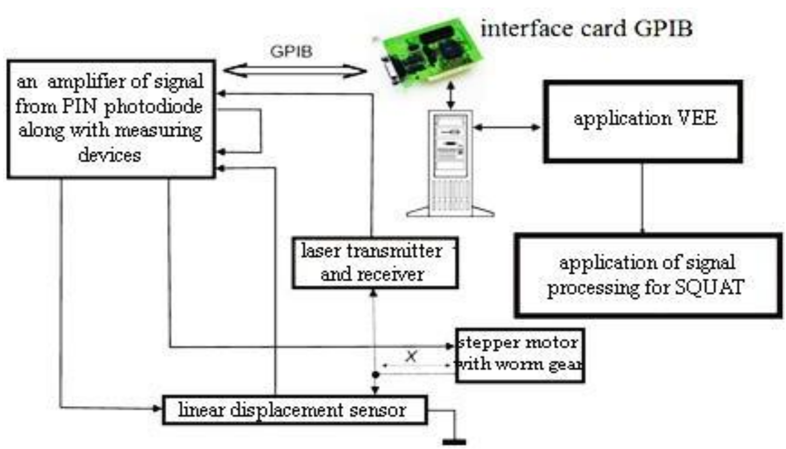


Fig.7. System configuration for laboratory set-up

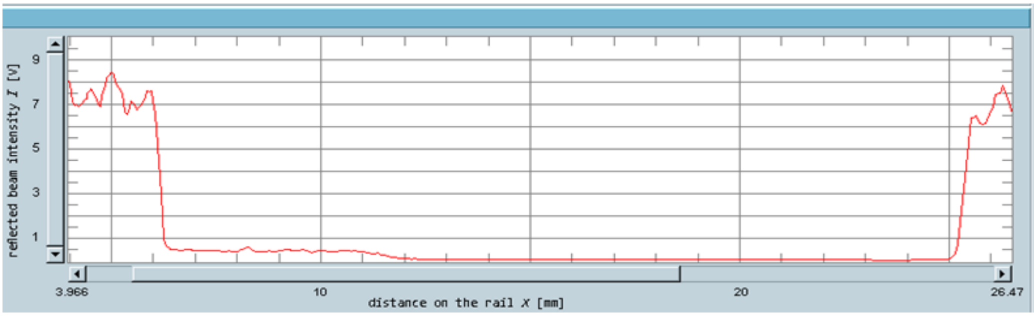


Fig. 8. The print-screen of application written in VEE environment with changes in light intensity for the defect with edge in the form of one step profile (fig. 6a) x = 21 mm in width and h= 5 mm in depth

5. Experimental results

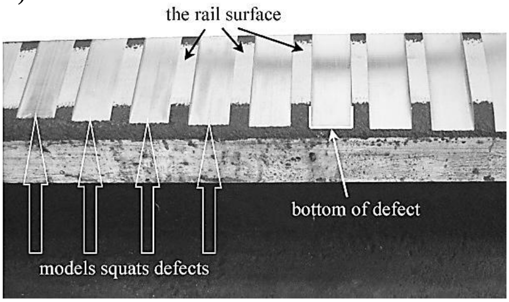
In experiment, the fragments of rail with both artificial surface defects and real squats were used. Artificial defects comprise defects with one, two and three steps on their edges and their depth changes from h = 0.5 mm to h = 5 mm with the step of 0.5 mm. The surface of every defect was polished and the bottom of defect is of 21 mm in width, fig. 9. Horizontal surface of defects and running surface of the rail are regarded as quasi mirrors. It means that mirror reflections dominate on these surfaces.

Laser beam incidence angle is usually chosen in experimental manner. During its determination the roughness of the surface is mainly taken into account. According to Łukianowicz (2007) the laser and detector should be positioned at $\theta_1 = \theta_2 \approx 60°$ angles towards normal (fig. 2). These settings ensure maximal sensitivity of detection and are practically independent of roughness of the surface.

When analysing changes in light intensity, it is possible to point characteristic areas which corresponds to specific regions of defects. Areas I and II (fig. 10a) correspond to the running surface of the rail. It means that laser beam is completely reflected from the surface, what allows for perfect detection of the beam by PIN detector. When laser beam reaches the edge of defect, it is reflected from the bottom of the defect and moves to areas III and IV (fig. 10a). These areas correspond to defects with one and two steps on the edge (see fig. 6).

Fig. 10b), c), d) and e) present light intensity after reflection from artificial defect registered by PIN photodetector. Fig. 10b), d) and e) show results of measurements for defect with one step on the edge (fig. 6a), x = 21 mm in width, and h = 5 and 2 mm in depth respectively and fig. 10c) for defect with two steps on the edge (fig. 6b), x_1 = 22.0 mm, x_2 = 20.4 mm in width, and for h_1= 1.2 mm, h_2 = 2.1 mm.

a)



b)

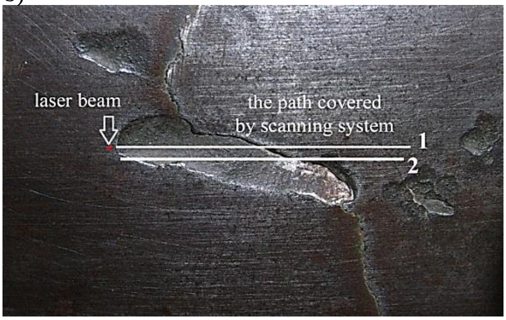


Fig. 9. Objects under analysis: a) artificial defect, b) real squat defect from fig. 1a

Measured light intensity strongly depends on the defect depth. It is also strongly dependent on the photodetector radiant sensitive area. This area should be larger when defect depth is greater. For depths $h \leq h_{s1}$, (where h_{s1}, h_{s2} are some characteristic values of flaw depth), the whole reflected beam reaches photodetector radiant sensitive area. When the defect is of $h \in (h_{s1}, h_{s2})$ in depth, then the part of reflected beam "escapes" from photodetector radiant sensitive area. For the depths $h \geq h_{s2}$, the whole reflected beam "escapes" from photodetector radiant sensitive area.

While analyzing the area IV in fig. 10, it is possible to notice that reflected light is completely "hidden" behind the step of the edge and does not reach a photodetector. This phenomenon occurs in all registered waveforms corresponding to changes in light intensity.

The real squat defect from Fig. 9 was also investigated. Measurements were performed for two path covered by scanning system. Fig. 11 shows measuring results. There is an analogy between artificial and squat defects.

The experimental results are in qualitative conformity with theoretical predictions presented in the previous section. Comparing the theoretical and experimental curves of changes in light intensity (fig. 5 and 10) for the standard rectangular defects, one can unambiguously identify individual regions of defects, on which laser beam falls. As a next step we plan to prepare a numerical procedure, which could fit theoretical curves of light intensity changes (defined as a spline functions) to the experimental data acquired during the scan of the railway rails. This is a way for determining the geometric parameters of defects' cross-sections. Moreover, the theoretical model will be developed by considering a diffusive scattering and interference phenomena on the micro-roughness of defects' surfaces.

6. Conclusions

Methods of surface defects detection used on railway lines are highly ineffective, hence, there is a need for further research, which could improve the diagnostic of both traditional railway lines as well as Warsaw underground lines (Hansen and Calvert, 2002). Presented laser scatterometry method can constitute a solution of this crucial problem.

The paper deals only with squats, which belonging to rolling contact fatigue defects. Statistics shows, that they dominate on the railway tracks. Simulation results and laboratory experiments performed for artificial and real defects confirm its effectiveness in detection of such defects.

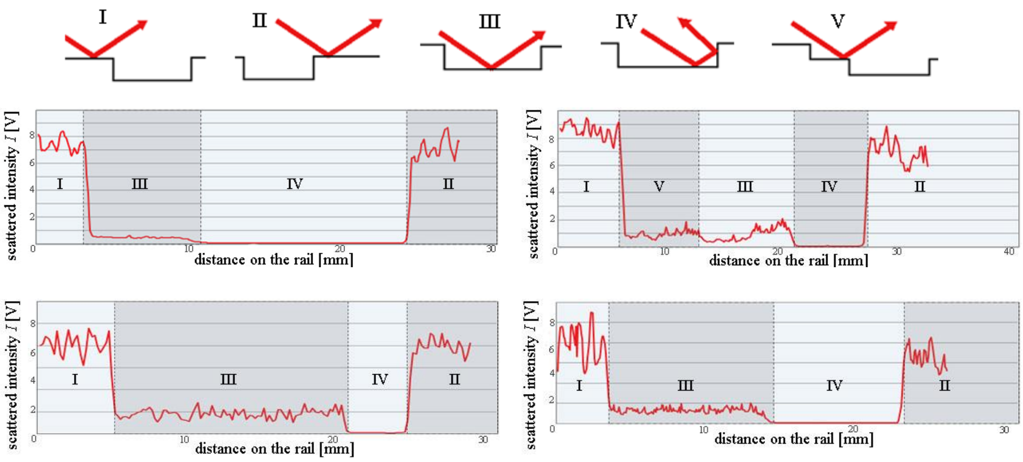


Fig. 10. Changes in light intensity reflected from artificial defects registered by detector a) presentation of areas of reflection in the defect, areas I, II – scanning on the running surface of the rail, III, IV-scanning on the bottom of the defect, V – scanning on horizontal surface of the step, b) defect with one step on the edge of $\boldsymbol{x}$ = 21 mm in width and $\boldsymbol{h}$= 5 mm in depth, c) defect with two steps on the edge of $\boldsymbol{x_1}$ = 22 mm, $\boldsymbol{x_2}$ = 20.4 mm in width and $\boldsymbol{h_1}$ = 1.2 mm, $\boldsymbol{h_2}$ = 2.1 mm in depth (as in fig.6), d) defect of $\boldsymbol{x}$ = 21 mm in width and $\boldsymbol{h}$= 1.3 mm in depth, e) defect of $\boldsymbol{x}$ = 21 mm in width and $\boldsymbol{h}$= 3.4 mm in depth

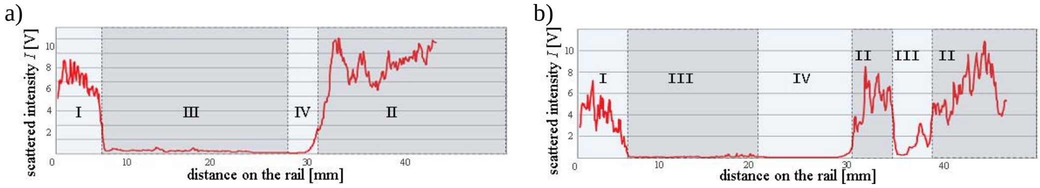


Fig. 11. Changes in light intensity measured by detector for the actual squat defect: a) for path 1 covered by scanning system - fig. 9b, b) for path 2 covered by scanning system - fig. 9b

The main advantages of proposed method are: contactless measurement procedure and almost unlimited speed of measurements. It is a significant argument to its application in high speed railway lines.

Authors, as pioneers in application of this method in detection of squat, notice the need for further development of this method. Firstly, in order to extend the area of examined rail head, multiple pairs of laser – detector should be added to the laboratory setup. It can be realized by linear set of these pairs placed perpendicularly to the movement of scanning system. Such solution allows a detection of other surface defects. Nevertheless the creation of the classification criterion for these defects remains an open problem (Lesiak and Migdal, 2009).

In next stage of research, authors are going to apply full laser scatterometry. The future model will consider both geometrical and wave optics aspects as well as realistic shapes of bottom of squats, what in turn will force authors to perform the 2D analysis instead of 1D analysis. It will entail both the application of sophisticated intelligent methods for analysis and image processing of scattered laser beam and reformulation of classification criterion for these defects (Bojarczak, 2013; Lesiak and Bojarczak, 2012).

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