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The Use of 3D Imaging in Surface Flatness Control Operations

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ABSTRACT

The paper presents a surface flatness control system designed for installation on a production line. Such a system allows the control of all blanks leaving the production line in terms of measuring flatness made in the conditions prevailing on the production line. The article discusses 3D imaging methods enabling the construction of a surface image. An analysis of imaging parameters for each method is presented. For the selected imaging method, an analysis of the imaging resolution is presented. An example of flatness measurement for a selected element after a welding operation is shown. The flatness measurement algorithm is discussed, and the results of measurements are presented. The results of measurements for selected two product groups are presented.

Keywords: vision system, 3D imaging, surface flatness, production quality control.

INTRODUCTION

Measurement of parameters of semi-finished products manufactured as part of technological operations carried out on production lines is currently a key element of maintaining production quality. In the work, special attention was paid to the issues of controlling the flatness of the surface of the workpieces. In industry, measurement methods are successfully used, which can be described as laboratory due to the way measurements are carried out. However, with increasing production capacities and the use of automation and robotization of production, such control is significantly limited. Of course, statistical methods are successfully used to assess the flatness of the surface on the basis of the measurement of a selected batch of manufactured semi-finished products using classical methods [1]. Traditionally, flatness assessment methods based on the reference plane are used, relative to which the parameters describing flatness errors are determined [2]. It is crucial to determine the reference plane and select the number of measuring points for the surface. In order to assess the flatness of the surface of the workpiece, it is necessary to collect information at specific measuring points on the surface [4]. The minimum number of measuring points needed for reliable surface mapping is determined by the ISO-TS12781 standard, and depends on the dimensions of the tested element. In industrial practice, the plane is most often mapped on the basis of measurements at points determined on the basis of the measurement strategy used in the company and the selection of the method of determining the grid of measurement points. The uniform distribution of a dense grid of measuring points allows a full description of flatness errors. However, it extends the measurement time. Minimizing the number of measurement points makes it possible to shorten the measurement time, but at the same time allows only an illustrative assessment of flatness. In the practice of industrial measurements, measurements using sensors are often used. The simplest measurement method is to use a measuring table and a dial indicator. On the basis of this solution, multisensor systems are built that allow for an illustrative assessment of flatness based on measurements at selected measurement points. Such measurements can be carried out using laser sensors. In both cases, the number of measuring points is limited. In laboratory conditions, the most commonly used measurement method is the use of coordinate measuring machines and algorithms developed by machine manufacturers [5]. Scientific papers also describe methods based on the use of an interferometer in measurements of straightness and flatness [6] However, the choice of measurement method depends on the task performed, the required measurement time and the shape and dimensions of the product being dimensioned.

An example of a technological operation considered in this work is the welding of bodies. As a result of welding, distortions occur on previously prepared and treated surfaces of semi-finished products. The “lean manufacturing” of the structure, currently commonly used in the industry, causes that the components have reduced wall thicknesses. At the same time, it is required to increase production efficiency. The combination of the strategy of “slimming” the product with the need to increase production efficiency leads to a change in the parameters of the process. However, these changes result in more product execution errors. As a consequence, a system of inspection of all blanks leaving the manufacturing station is needed in order to quickly identify potential manufacturing defects.

Another example of a technological operation in which surface flatness errors occur is injection molding methods. A wide range of materials used on injection molding machines makes it necessary to accurately match the injection conditions and the method and time of cooling the injection mold to the material used in the production process. In practice, however, there are differences between batches of the same type of material, its moisture content and chemical composition. This causes disturbances and, consequently, deformation of usable surfaces injected into mold as a result of uneven shrinkage of the material. When multi-nest molds are used, it is not possible to conduct full control in laboratory conditions.

The discussed examples of technological operations were the reason for starting work on the flatness control system for selected products intended for installation in industrial conditions. The assumption was to develop a system allowing the measurement of the manufactured semi-finished product immediately after the technological operation. The product surface analysis time should be short enough to measure all products leaving the line in turn. The article presents a proposal for an imaging method based on the construction of a 3D image of the surface. Next, selected algorithms for flatness control for exemplary industrial surfaces are presented. The method is discussed on the examples of an injection molded product prone to uneven material shrinkage. As a consequence, collapse and cavities are visible on the usable surfaces, as well as flashes at the boundaries of the injection mold.

The paper presents a method of constructing a three-dimensional image of the surface for selected products. The issue of imaging resolution and the selection of resolution for the task at hand were discussed. Analysis of the 3D image, in the scope of initial image filtration and measurements carried out with the performance expected on the production line and the presence of disturbances occurring in the industry, is presented. It has been proven that it is possible to measure flatness in flow mode directly on the line. Guidelines for the selection of operating parameters of the triangulation system used in industrial measurements were also indicated.

METHOD OF MEASUREMENT

The design of the measurement system for assessing the flatness of the surface began with the analysis of imaging methods capable of recording a 3D image of the surface. An additional assumption was made regarding the dimensions of the imaged surface. It was assumed that for most measuring tasks it would be a surface measuring 180×400 millimeters. For such a selected surface dimension, the ToF (Time of Flight) method, stereovision and laser triangulation were evaluated.

The ToF method is based on measuring the time of propagation of the wave from the camera transmitter to the imaged surface, its reflection and reception of the wave reflected on the sensor matrix. Time analysis allows you to determine the distance of each measuring point from the camera. It allows for very fast acquisition of three-dimensional images [7, 8] . Acquisition time can be less than 1 millisecond. In this technology, however, there is a certain limitation in the selection of sensor matrices. Industrial versions are characterized by a small number of sensors placed on the matrix. The resolutions of the matrix are currently e.g. 640×480, e.g. in Basler cameras. This means that the distance between the measuring points on the imaging plane for the accepted imaging field in the *OX* and *OY* axes can be up to:

$$R_{px} = 180 \text{ mm} / 480 \text{ pixel} = 0.38 \text{ mm/pixel} \quad (1)$$

$$R_{py} = 180 \text{ mm} / 640 \text{ pixel} = 0.28 \text{ mm/pixel} \quad (2)$$

The spatial resolution of Rpx and Rpa determined in the direction of both axes on the measured plane depends on the position of the measured object relative to the sensor matrix. For such a solution, it is possible to obtain the spacing of measuring points on a plane at a distance of 0.3–0.4 mm. However, due to the angular propagation of the measurement beam generated by the camera, the distances between points increase significantly. The resolution in the direction of the OZ axis describing the measurement of the height of the object, marked as Rpz, depends on the parameters of the electromagnetic wave propagation time measurement system emitted by the camera. However, determining the height of each point is burdened with a very large error. The camera manufacturer states that this parameter is +/– 1 millimeter. This resolution does not allow the measurement of most flatness errors for welded or injection molded parts.

In the stereovision method, a system of two cameras simultaneously records the image of the same surface in order to reconstruct its three-dimensional representation. The imaging resolutions on the imaging plane in this method can be an order of magnitude higher than in ToF. However, this method is based on combining 2 images on the basis of characteristic points determined in both images [9]. Taking into account surfaces after mechanical treatment, having the character of mirror surfaces, the three-dimensional image recorded by this method is often burdened with a large number of interferences. These disturbances can be eliminated by applying surface structures in the form of a spray, e.g. powder. In industrial environments, with the required short lead time of measurement in flow-through mode, the use of this method would significantly complicate the flatness control process. The solution would be to use a stereovision system with structured lighting, e.g. in the form of fringes displayed on the imaged surface. This significantly reduces the number of interferences. However, it requires tests for each of the surfaces taking into account the assessment of the influence of the material and geometric structure of the imaged surface [9, 10].

The SFF method is based on the use of information about the sharpness of the recorded image. It requires stopping the subject under examination and recording a series of images when the focal plane is repositioned. The resolution in this method depends on the number of images recorded. It is used in laboratory conditions and in the field of microscopic examinations. Therefore, there is no implementation potential in vision systems operating on production lines (Fig. 1).

The laser triangulation method was chosen to perform the task, enabling the construction of an image during the movement of the product under a stationary triangulation system. In this method, the surface is illuminated by a linear laser beam. The image of the illuminated surface is recorded by the camera. Then, based on the information about the angular alignment of the laser beam relative to the optical axis of the camera and the geometry of the camera position relative to the laser, a height profile describing the surface in the place of illumination by the laser beam is determined [12, 13]. The research uses geometry in which the linear laser beam is set perpendicular to the tested surface. The optical axis of the camera is set at an angle to the surface to be tested. The choice of camera angle depends on the expected measurement resolution. The measurement resolution additionally depends on the sensor matrix used in the camera and the selected optical system [14]. Figure 2 shows the configuration of the vision

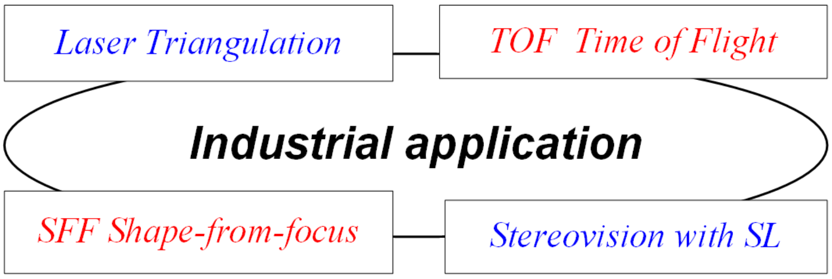

Fig. 1. Imaging methods used in industrial tasks [11]

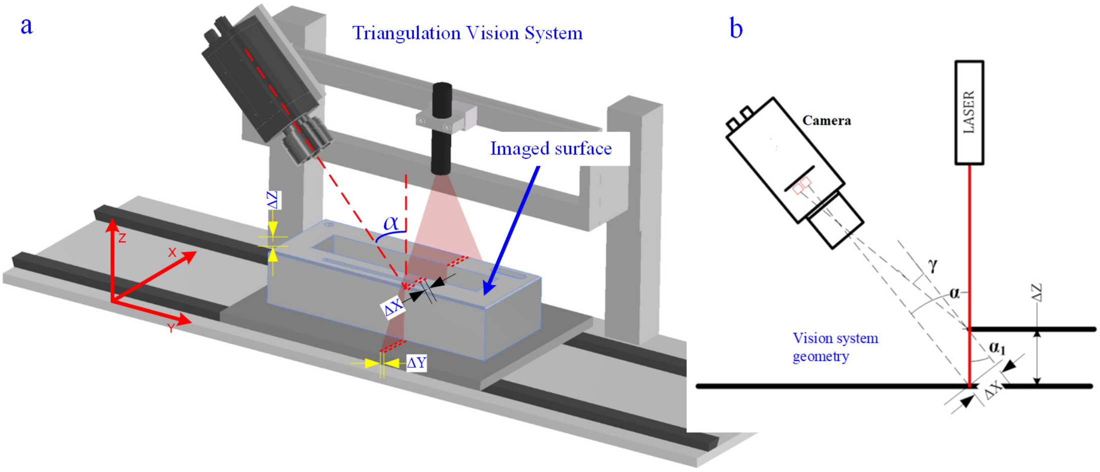

Fig. 2. Measuring station: a – triangulation vision station, b – vision system geometry

system. The laser illuminates the surface of the tested object moved on guides. The displacement along the OY axis between successive measurements is defined as the resolution in the Y axis and is marked in the work as ΔY.

The number of measurement points forming a single height profile corresponds to the number of columns on the sensor matrix used to record the image of the laser line. The number of profiles designated for the object depends on the shift in the Y axis between the registration of subsequent profiles. In the subsequent cells of the image matrix, the height information described in the elevation profile is stored. The coordinate system was adopted in such a way that the X axis was parallel to the laser plane. The Y axis is assumed according to the direction of movement of the imaged object during the determination of subsequent height profiles. For a 3D imaging system, the resolution is determined in the direction of the three axes of the coordinate system associated with the measurement station. The following designations were adopted in the work:

- ΔX – resolution in the direction of the X axis, i.e. along the laser line,
- ΔY – resolution in the direction of the Y axis, i.e. the axis perpendicular to the laser line and at the same time the direction of movement of the tested object,
- ΔZ – resolution in the direction of the Z axis of the vision system coordinate system (minimal recognizable change in the height of the object).

The resolution is determined on the basis of the geometry presented in Figure 2b. It uses an approximation in which we assume that the angle α is equal to the angle α_1. In fact, the angle $\alpha_1 = \alpha - \gamma$. In 3D vision systems, resolutions of the order of $\Delta X = 0.1$ mm or more are used. Consequently, such simplification does not significantly affect the resolution of the measurement. The resolution of Z-axis imaging is determined from the formula:

$$\Delta Z = \Delta X / \sin(\alpha) \tag{3}$$

where: ΔZ – resolution in the direction of the Z axis (recognizable change in the height of the object), ΔX – resolution in the X direction, α – the angle between the optical axis of the camera and the optical axis of the laser.

The research assumes that the maximum dimensions of the object are no more than 180 x 400 mm. This object is imaged on a sensor with a width of 1500 pixels. The resolution was selected assuming:

- Angle $\alpha = 30°$ to $81°$ – camera angle,
- FOV = 180 mm – imaging field in the X axis expressed in mm,
- RM = 1500 pixels – X-axis imaging field expressed in pixels.

The resolutions for the adopted geometry are determined from the following formulas:

$$\Delta X = 180 \text{ mm}/1500 \text{ pix} = 0.12 \text{ [mm/pixel]} \tag{4}$$

$$\Delta Y = 0.4 \text{ mm} \tag{5}$$

$$\Delta Z = 0.12 \text{ [mm]} / \sin(75°) = 0{,}12 \text{ [mm]} \tag{6}$$

Each square millimeter of the surface is imaged using 20 measuring points. The camera has been set at an angle of $\alpha = 75°$ which allows to obtain a resolution of 0.12 mm. The choice of camera angle depends on the design of the measuring station. Increasing the resolution of the Z-axis height measurement on the surface can be achieved by increasing the resolution of the sensor array or by increasing the angle of the camera relative to the laser plane. For the adopted range of angle α, the characteristics variability resolution in the Z axis as a function of angle α (Fig. 3) were determined.

Imaging with this resolution makes it possible to cover every square millimeter of the surface with 20 measurement points. The number of points can be minimized to reduce analysis time. In the case of the conducted research, the analysis of each made semi-finished product assumed a time of 1500 ms. 3D imaging was performed for an aluminum body welded from two parts. As a result of errors occurring in the welding operation of the element of the two elements visible in Figure 4 on the upper part of the body, flatness defects may have occurred. The aim of the project was to develop a system that allows to control the flatness of all bodies produced on the production line immediately after the welding operation and cooling of the body. The imaging was carried out using a laser emitting electromagnetic radiation with a length of 658 nm and a maximum power of 20 mW (Fig. 5a). For the surface of the machined aluminum, the power was reduced to 30% of the maximum laser power. Reducing the laser power made it possible to reduce the reflection of the beam from the surface of the processed aluminum and to reduce the interference visible in the 3D image (Fig. 5b). Figure 5a shows the upper surface of the albumin body illuminated by a laser beam. Near the beam, a slight scattering of emitted radiation is visible. However, this does not affect the measurement of the height of points distributed on the test surface. Figure 5b shows a three-dimensional image of the upper surface of the body. This is a raw image that has not been filtered at this stage.

The imaged surface shown in Figure 5a is not perpendicular to the laser plane created by the line beam. Such an approach makes it possible to assess flatness regardless of the angle of the object on the workstation and regardless of the angle of the vision system used in the image acquisition process. This approach makes it easier to carry out

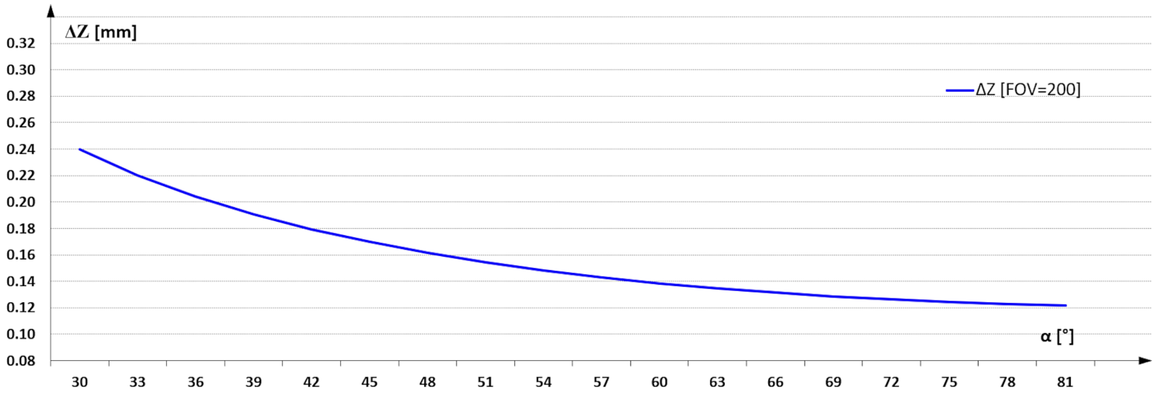

Fig. 3. Z-axis imaging resolution as a function of angle α

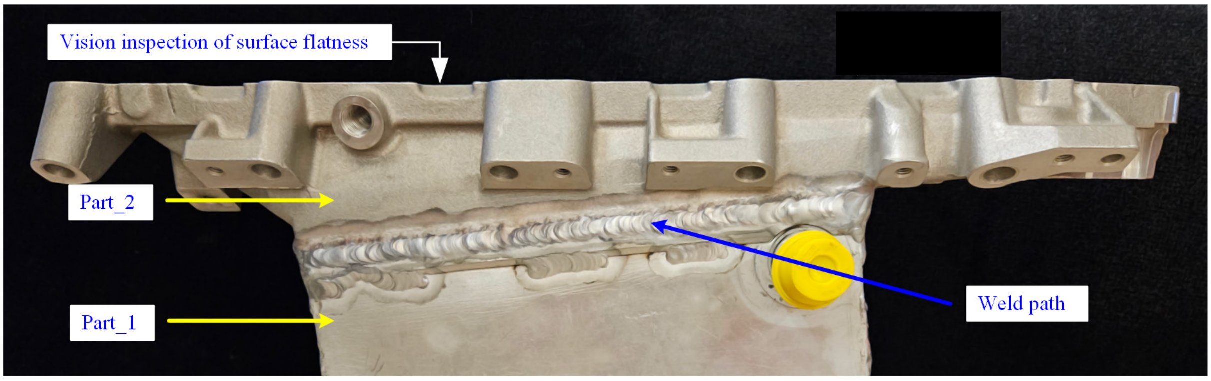

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Fig. 4. Aluminum body welded from two parts subjected to 3D imaging

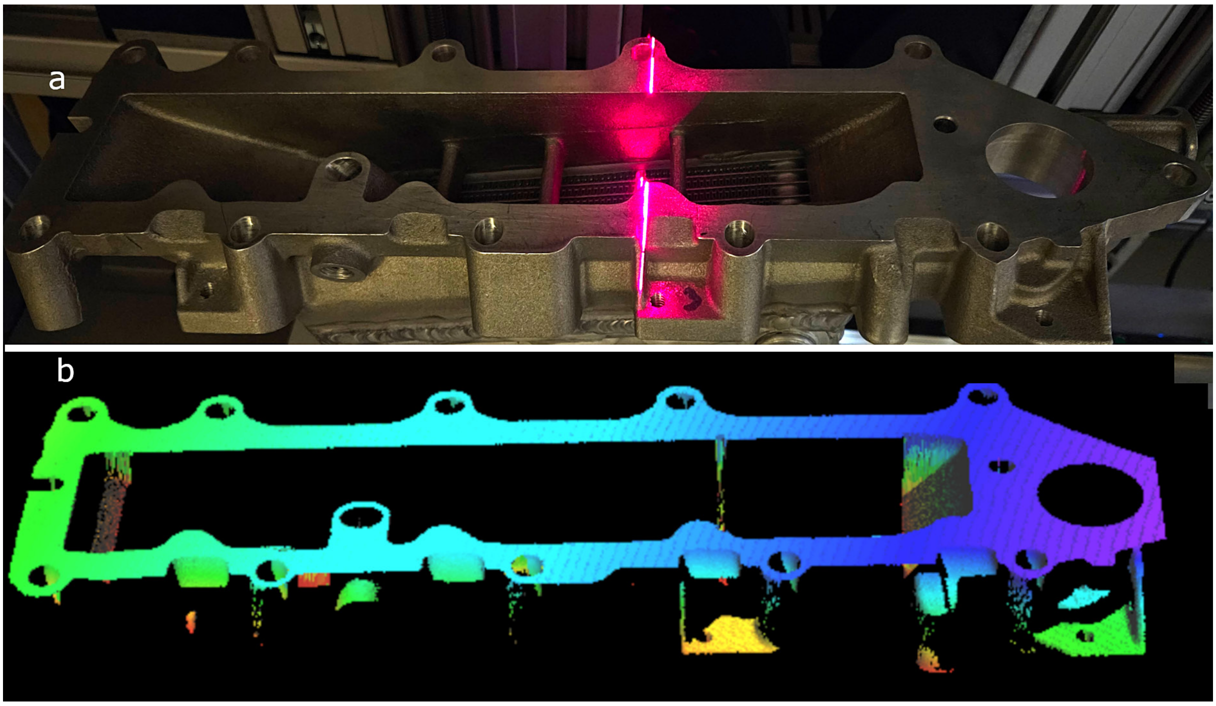

Fig. 5. Surface imaging: a – illumination of the surface with a laser line, b – 3D image of the surface

measurements at manufacturing stations and on industrial conveyors. The colors shown in Figure 5b represent the scaling of the height of the points that make up the surface as recorded by triangulation. The surface thus imaged is described by 20 measuring points for each square millimeter. This is a significant extension to the methods based on coordinate measuring with a limited number of points [15–18]. The use of 3D imaging enables a surface description based on a significantly larger number of points.

In the next stage, the recorded three-dimensional image was subjected to a filtering operation enabling the removal of interference appearing on the edges of the machined planes resulting from the refraction and scattering of the laser beam. Next, the point areas described as ROI (Region of Interest) were defined. The points in these areas were used to determine the plane that will be used in the measurements as a reference plane. The flatness error will be determined with respect to the reference plane. Figure 6 shows the ROI areas numbered from 1 to 8. They should be spaced evenly over the entire controlled surface. You can also use all the points in the image to determine this plane. However, this doubles the analysis time for the presented example. To determine the plane, the method of minimizing the sum of

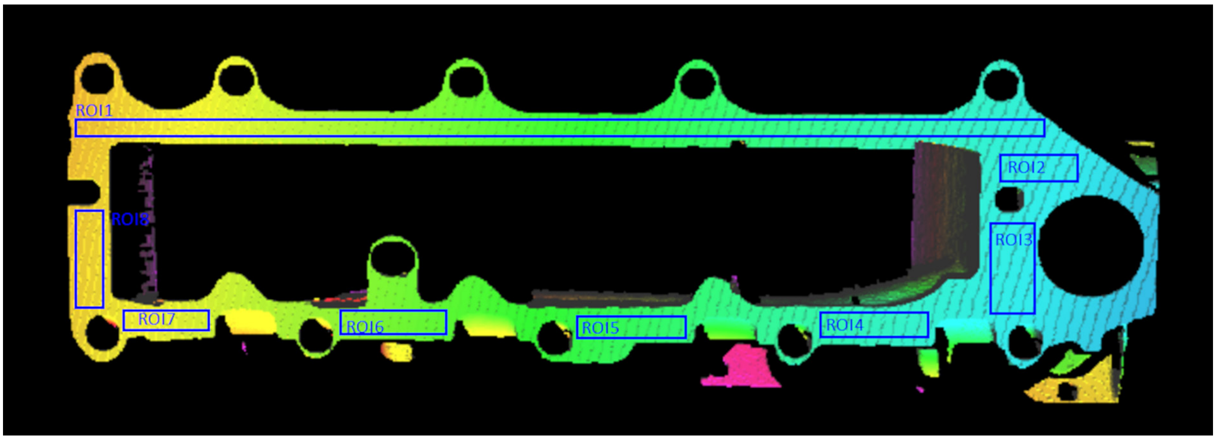

Fig. 6. 3D surface imaging with marked ROI areas

squares of the distance of measuring points covered by ROI areas from the determined plane was used. An image of the reference plane plotted on the 3D image is shown in Figure 7. The figure also indicates the flatness errors visible in the 3D image, located for the selected example in the left and right parts of the welded body. A significant deviation of the actual plane from the reference plane is visible. The three-dimensional image prepared in this way will be used to measure the deviation along the selected profile on the body.

A surface imaging method based on laser triangulation enables imaging of various materials. However, it is important to choose imaging parameters, e.g. laser illuminator power, laser operation mode and image acquisition time. These parameters should be selected experimentally for each of the imaged surfaces. Incorrect selection of parameters may result in the appearance of point interference in the image resulting from directional reflection of the laser beam or its excessive scattering. In both cases, the image of the distorted beam visible on the surface makes it impossible to determine the coordinates of its location and, consequently, the possibility of surface reconstruction. The image of the laser beam designed on plastic materials changes as a result of irregularity of reflection and dispersion depending on the parameters of the geometric structure of the surface. In addition, it depends on the color, density and grade of the material. These parameters may cause complete scattering or absorption of the beam, which will prevent the construction of a surface image. An example of imaging a plastic cover is shown in Figure 8.

RESULTS

3D image analysis allows you to determine selected product parameters, e.g. flatness deviations using all points forming the surface. With a designated reference plane, it is possible to check the distance between the reference plane and the points describing the actual surface in the 3D image. In such an approach, the point furthest from the reference plane would be sought. It is also possible to use a more targeted algorithm, e.g. measuring the distance selected for a selected group of product surface points. For example,

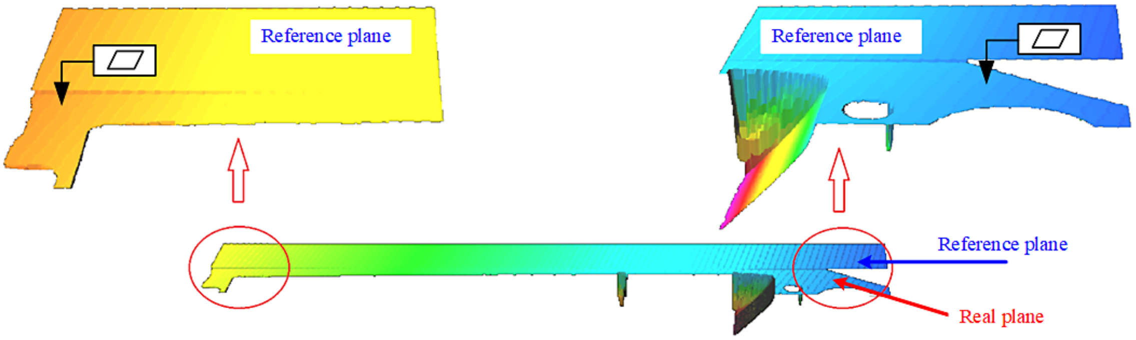

Fig. 7. 3D surface imaging with marked deviations of the actual surface relative to the reference surface

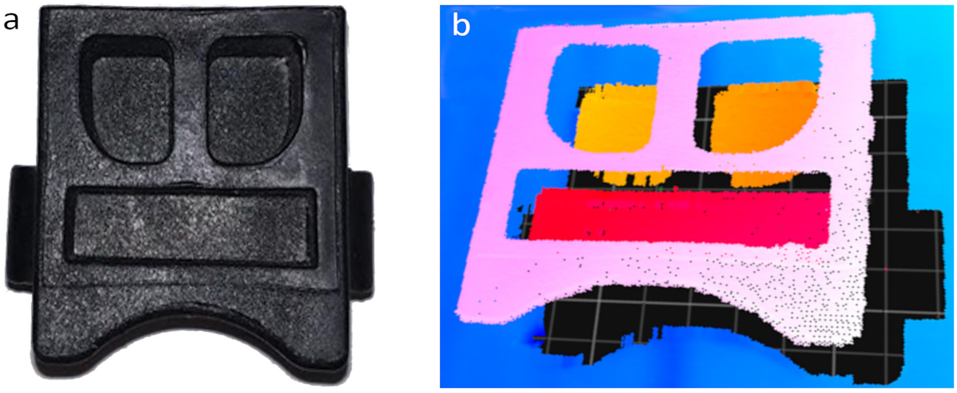

Fig. 8. Three-dimensional image of the surface of an element made of plastic

inspection can be carried out along the selected profile or in places most technologically exposed to deformations occurring during welding. The figure below shows the result of measuring the flatness deviation along the profile positioned on the surface of the body in the manner presented in Figure 9a. Deviation is defined as the distance of each point along the designated profile from the reference surface. It is marked on the graph as ΔL and is determined in millimeters.

A measurement profile containing 890 points between points P1 and P2 was defined in the 3D image. It was positioned along the plane made on the upper plane of the body in the manner visible in Figure 9a. As a result of the welding operation of the body, its central part was pushed upwards. The sides of the body were pulled down. These errors result from the setting of the welding path of the two elements of the body presented in Figure 4. The characteristic shown in Figure 9b shows the distance from the reference plane Thus, it represents the absolute value of the flatness deviation. For the selected measuring profile, key parameters defined in the body welding quality control procedure are determined, e.g. maximum deviation value. The analysis time using the profile is about 150 milliseconds. The three-dimensional image allows you to measure in selected places of the inspected surface or along any profile defined on the surface. This depends on the product and the requirements of the quality control department. In the case of analysis of all points forming a three-dimensional image, the points of the actual surface are searched for the most lowered and the points most raised relative to the reference surface. The next figure shows the surface made on the injection molding machine with a visible flatness error resulting from shrinkage occurring during the cooling operation of the material (Fig. 10). The figure indicates as Pmin the area on the surface with the points most lowered relative to the reference plane. The

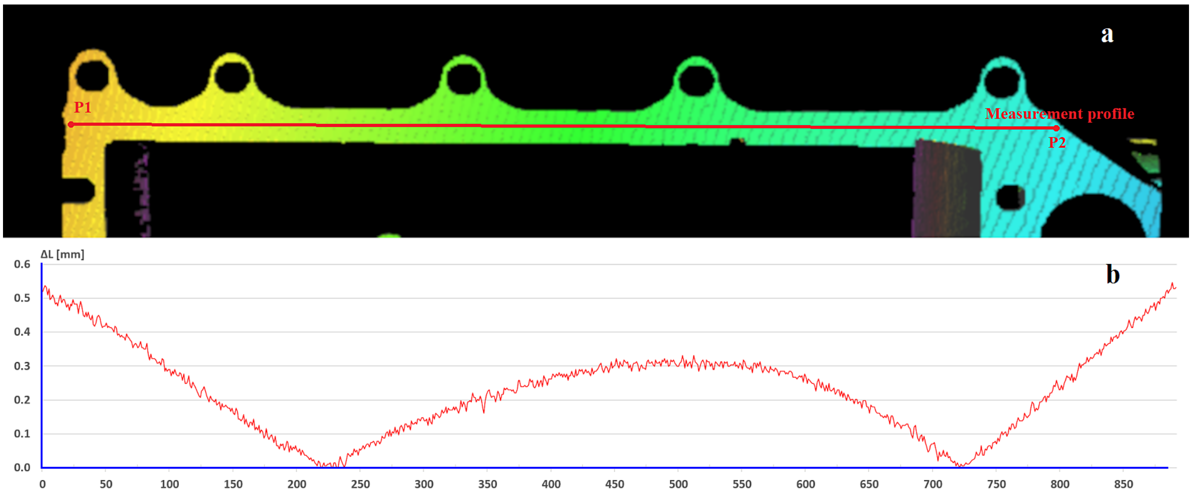

Fig. 9. Measurements using a three-dimensional surface image: a – view of the selected measurement profile, b – flatness error distribution along the profile

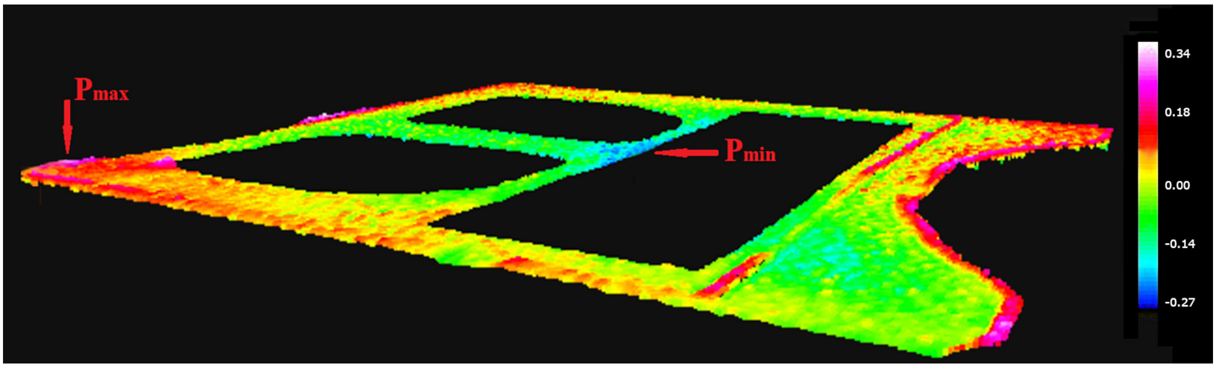

Fig. 10. Analysis of all points on the controlled surface – determination of points

designation Pmax, on the other hand, defines the most elevated area. That is, the absolute height of each point has been replaced by the distance of that point from the reference plane. As a result, you can clearly see the depression in the middle of the object and the distribution of flatness error over the entire inspected area. These errors are marked in the figure with colors corresponding to the value of the determined flatness deviation. The flatness analysis was performed for all points of the recorded image, which extended the measurement time to about 800 milliseconds.

CONCLUSIONS

As part of laboratory work and industrial implementations, the possibility of using three-dimensional imaging in the operation of controlling the flatness of the surface has been proven. As part of the research, it was verified that it is possible to build a specialized system designed for the expected resolution of flatness deviation measurement. This requires the design of the vision system, the selection of hardware solutions to obtain the expected imaging resolution. The spatial resolution presented in the work, which allows the determination of 20 measuring points for each square millimeter, allows for a detailed description of the surface. This is a significant extension of the surface description capabilities and an increase in resolution compared to the industry-based systems based on the use of point sensors spaced above the tested surface. Three-dimensional image allows you to use all points of the image or selected areas on the surface in the analysis of flatness.

The time to perform a full-image analysis ranges from 500 to 1000 milliseconds. For analysis in selected profiles, this time can be reduced to approximately 150 milliseconds. The use of an imaging system therefore allows the control of all products manufactured on production lines. In the process of designing a vision system, special attention should be paid to the interaction of the laser beam with the surface of the imaged product. It is necessary to choose the laser power, the optical system focusing the beam to the conditions of installation at the control station. Then select the camera and lens for the required imaging field and check the possible imaging resolution. Launching the system also requires the development of an image analysis algorithm and the development of a measurement algorithm.

When considering the development of this method of imaging and flatness measurements, it would be necessary to develop a method for verifying the measurement uncertainty for a vision system operating in specific industrial conditions. This method should consider the influence of the movement of the object and the influence of the drive and transmission system on the measurement results. In many cases, a measurement standard can be used for a vision system. Measure the standard on a CMM and then check how the same standard is reproduced in a three-dimensional image under the given process conditions.

The scope of design and software work at the launch of the 3D imaging system is much wider. However, the use of this technology allows for a very flexible and detailed check of surface parameters. In addition, the 3D image can be used to carry out additional measurements, e.g. to determine selected geometric measurements such as diameters, lengths, etc. It is therefore a technology that significantly dilutes the possibilities of product control directly on the production line.

REFERENCES

1. Sałaciński T., SPC. Statystyczne sterowanie procesami produkcji. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2016.
2. Adamczak S.: Pomiary geometryczne powierzchni. Zarysy kształtu, falistość i chropowatość. Wydawnictwa Naukowo Techniczne, Warszawa 2008.
3. Filipowski R., Lechniak Z., Zawora J.: Flatness error of a plane in the hand operated Coordinate Measuring Machine. Mechanik, 89(2), 2016: 100-104.
4. Bartkowiak T., Gessner A.: Determination of minimal sample size for flatness error estimation by means of coordinate measurement. Mechanik, 87(8-9), 2014: 7-16.
5. Filipowski R., Lechniak Z., Zawora J.: Flatness error of a plane in the hand operated Coordinate Measuring Machine. Mechanik, 89(2), 2016: 100-104.
6. Zagajski P., Dreszer K. A.: Laser interferometer use in measurements of geometrical sizes and constructional agricultural machines. Inżynieria Rolnicza, Vol. 12, No. 11(109), 2008: 255–262.
7. Adamczyk, J., Sioma A., Automatization of workspace control based on ToF technology. Proc. SPIE 10808, 108081E-1–108081E-9, 2018.
8. Junttila, V., Kauranne, T., Finley, A. and Bradford,

J.B., Linear models for airborne-laser-scanning-based operational forest inventory with small field sample size and highly correlated LiDAR. IEEE transactions on geoscience and remote sensing, 53(10), 2015: 5600–5612.

9. Di Stefano L., Marchionni M. and Mattoccia S., .A PC-based real-time stereo vision system. Machine Graphics & Vision, 13(3), 2004: 197–220.
10. Brown, M.Z., Burschka, D. and Hager, G.D., Advances in computational stereo. IEEE Trans. on Pattern Analysis and Machine Intelligence, 25(8), 2003: 993–1008.
11. Sioma, A., 3D imaging methods in quality inspection systems. Proceedings of SPIE - The International Society for Optical Engineering, Vol. 11176, 2019.
12. Amann, M.C., Bosch, T., Lescure, M., Myllylä, R. and Rioux, M., Laser ranging: A critical review of usual techniques for distance measurement. Opt. Eng. 40(1), 2001: 10-19.
13. Sioma, A., Laser illumination in triangulation vision systems. Photonics applications in astronomy, communications, industry, and high energy physics experiments, Vol. 12040, 2021.
14. Sioma, A., Geometry and resolution in triangulation vision systems. Photonics applications in astronomy, communications, industry, and high energy physics experiments. Proceedings of SPIE, Vol. 11581, 2020.
15. Lakot S., Gorog A., Flatness measurement by multipoint methods and by scanning methods. Ad-Alta J.
16. Collins T., Bartoli A., Infinitesimal plane-based pose estimation. International journal of computer vision, 109(3), 1-36 (2014).
17. Balazs M., Assessment of flatness error by regression analysis. Measurement, 171, 2021: 108720.
18. Raghunandan R. Venkateswara Rao P., Selection of sampling points for accurate evaluation of flatness error using coordinate measuring machine. J. Mater. Process. Technol., 202, 2008: 240–245.