

## ASSESSMENT OF CUTTING EDGE DEFECTS USING A VISION METHOD

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**Abstract:** The paper discusses a vision method of assessment of laser cutting edges and surfaces of metals. It presents an analysis of the defects that occur at the edges and surfaces of components cut out in laser technology. It discusses in detail examples of defects, their causes, and methods of preventing their occurrence in the cutting process. The paper presents a vision method for the identification and assessment of defects based on selected examples. It also discusses a method of constructing a three-dimensional image of a product, issues related to the resolution of the vision system and the resolution of laser beam analysis, and methods of image analysis.

**Key words:** 3D Vision System, Image Processing, Surface Defects, Process Control, Quality Control

### 1. INTRODUCTION

The purpose of this paper is to present methods for the identification and evaluation of surface and edge defects formed during laser cutting. The process of detection and identification of defects that occur during cutting is part of the control carried out on production lines usually by humans. The method of automating the control process discussed in this article was developed for a selected technological process. i.e. laser cutting, based on studies of defects that occur during the machining of metals. A method for constructing a three-dimensional image of the product and an image processing algorithm that allows observation and evaluation of the defect are discussed (Kowal and Sioma, 2009,2010; Gawlik and Sioma, 2004). Such an image contains information about the actual dimensional parameters of the product and allows their control immediately after technological operations. These days, in the conditions prevailing on the production line in mass production, statistical control is used in order to evaluate product parameters (Sioma, 2011a, b). Accurate measurements are also performed at random, in measurement laboratories. The solution presented in this work allows monitoring of all products leaving the process and practical application of the "zero defects" method. It also allows the use of feedback information about possible defects in the product in the process of controlling the technological parameters of the process.

The machining tools used in the industry are equipped with control systems capable of carrying out technological operations in accordance with a developed programme, including quality control of its implementation. However, there may still occur manufacturing defects associated with the type of workpiece material, programmers' errors, operators' technique, and characteristics of the machining method employed in the technological process (Sioma and Struzikiewicz, 2011; Oczóś and Liubimov, 2003; Pawlus, 2006).

The paper presents typical defects that occur in the cutting of metals with the use of a laser. The advantages of this method of machining include: precision of the cut, quality of the edges obtained, cutting speed, and a narrow range of temperature im-

pact. In addition, the following pros should be mentioned: material savings resulting from the small dimensions of the gap, a wide range of workpiece materials, and non-contact machining. Technological practice, however, shows that laser metal cutting produces defects also on the machined surfaces and edges. Defects can be created as a result of damage to the components of the machine (laser cutter) or a bad choice of parameters in the process.

One of the causes may be the wear of laser head nozzle or damage to the nozzle in contact with the workpiece material. The operating conditions of a laser cutter are defined by its boundary parameters, such as data regarding the range of laser power or the thickness of the workpiece material. Prior to starting work, the operator selects process parameters on the basis of technology tables implemented into the control system of the machining tool. Technology tables together with the available labour rules allow the operator to prepare a programme for the implementation of the cutting process. At this stage, the operator must pay attention to the parameters which affect correct execution of the cutting process, such as contour cutting sequence, direction of cutting, burn-through, entry positions, type of contour, corners, collisions between the machined pieces and the head, and arrangement of the table ribs.

For example, the position of a burn-through point is changed if the operator decides that the programme had arranged them too close to the cutting edge. However, if the burn-through point is moved too far away from the edge, the process will become longer and create additional costs, which, in turn, increases the price of the product itself. Workmanship of the cutting edge also depends on the knowledge and experience of operators. Many experienced operators build their own technology tables based on observation of the results produced by their machine. On the basis of work carried out in the industry, a description of the typical defects that occur on the edges and surfaces of cut-out pieces has been prepared.

The defects shown in the figures are described, along with their causes as well as methods of preventing their occurrence in the cutting process. The most basic and common geo-

metric shape cut with laser machines are circles. Cutting circles is mostly intended to eliminate the need for additional technological operations such as routing, drilling or reaming. However, the technological capabilities of the cutter and the required tolerances of the hole must be noted. One of the principles used in laser cutters when it comes to cutting holes is to verify whether the hole diameter is greater than or equal to the thickness of the material (Fig. 1):

$$\varnothing \geq g \tag{1}$$

where:  $\varnothing$  – hole diameter,  $g$  – thickness of material.

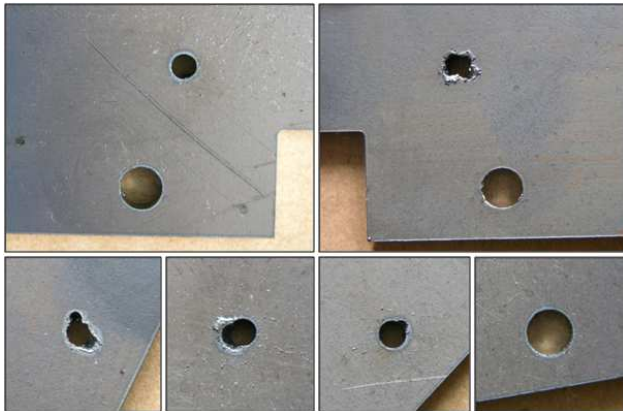


Fig. 1. View of holes made in steel

Depending on both the thickness and type of material used to manufacture a product, that principle may be abandoned and a test cut performed instead. However, failure to apply that rule leads to deterioration of the edge of the hole, which, in turn, leads to deformation of the hole.

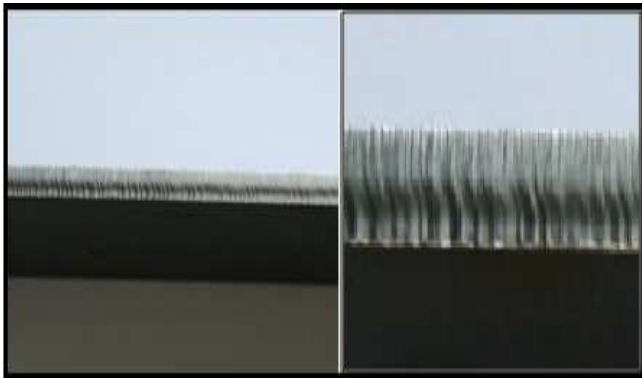


Fig. 2. Example of a defect on a cutting edge

Another example is the quality of a cutting edge. If the pieces are made of thin sheet metal, the edges are sufficiently accurate, which makes it possible to omit additional finishing operations such as grinding.

However, as thickness of the material increases, quality of the edge decreases, which also is closely related to the type and grade of the material machined. An example of a defect on an edge is shown in Fig. 2.

Another disadvantage observed during machining in the formation of welds, teeth, and, consequently, the lack of proper cutting of the material. Such a defect appears on the surface

of the material in case of wrong selection of laser power. An example of such a defect is the edge in Fig. 3. That defect also occurs when the working gas pressure drops or in case of an error in the setting of the laser beam focus. This requires additional repair process and adjustment of laser power.



Fig. 3. A defective cutting edge

Another example of defects are those caused by poor preparation of the laser work programme. A cut-out piece may be held by the grid in such a position in which it is damaged as a result of the laser cutting of successive pieces.



Fig. 4. Damage to the surface of the piece

Another defect that occurs during cutting is the formation of burr on the cutting edge. Burr is the presence of roughness on the edge. The causes of this defect are usually insufficient laser power, insufficient gas pressure, or incorrect focusing of the laser beam.



Fig. 5. Burr on cutting edges

In conclusion, the causes of defects on the edges and surfaces of the material being cut in laser technology usually include: dirty lens of the head, poorly chosen technology table, incorrect position of the laser beam focus, erroneously selected cutting speed, incorrectly chosen laser power, and worn or damaged table ribs.

Methods for improving the quality of edges and surfaces made by laser cutting include: proper selection of technology tables, laser lens cleaning, cutting head speed control, laser power control and adjustment of the laser beam focus, replacement of damaged ribbing of the table, cleaning of the surface of the material, and proper mounting of the material.

## 2. CONSTRUCTION OF PRODUCT IMAGE

The paper presents a method that enables automatic quality control of laser cut pieces. Quality control of the edges and assessment of the defects formed on surfaces was carried out using a specialized vision system. The construction of a vision system requires several steps, as a result of which successive parameters of the system's operation are chosen (Bednarczyk and Sioma, 2011; Tytko and Sioma, 2011; Sioma, 2010).

The first stage is the selection of the geometry of the system, i.e. camera and laser arrangement relative to the surface of the workpiece. The paper discusses a geometry in which the sensor of the vision system is set at angle  $\alpha$  relative to the surface of the measuring table. For the selected geometry, a method for determining the measuring resolution of the vision system is presented. It should be noted that in the selection of a vision system for specific measurement requirements, such as the measurement resolution recommended in the assessment of surface defects, selection of an appropriate optical system, i.e. focal length and type of the lens, and of an appropriate resolution of the vision system sensor, will also be necessary. In the presented geometry, the optical axis of the camera is not perpendicular to the surface of the measuring table and the plane of the test object's base (Fig. 6a).

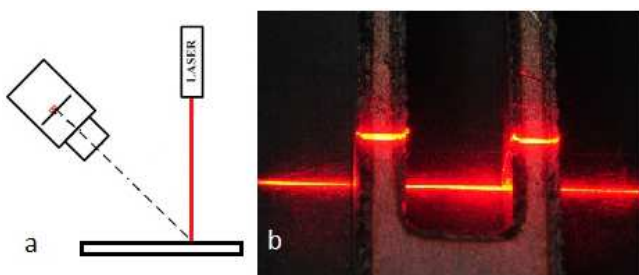


Fig. 6. Geometry of a vision system - camera and laser cooperation

For the presented geometry of vision system settings, the cross-section of the workpiece viewed in the camera and effected by the laser beam is parallel to axis Z in the coordinate system of the measuring table. It is also parallel to the plane of the laser displayed on the test object. That cross-section is observed by the vision system at a certain angle that had been chosen for this task (Fig. 6b). As a result, mathematical processing is required to enable conversion of the geometry of the cross-section in the image created by the laser beam in order to obtain an actual cross-section and then construct a three-dimensional image of the tested object. In the next stage of vision system

configuration, it is necessary to set the vision system resolution in the adopted configuration. As a result of change in object height, the laser line image moves on the CMOS camera sensor. Designation of vision system resolution consists in determining such minimum change in object height, described by the  $\Delta Z$  parameter, at which the laser image is observed to move exactly by one row of pixels on the camera sensor (Fig. 7).

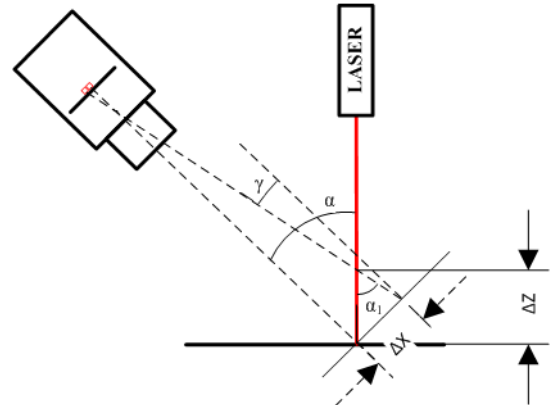


Fig. 7. Determination of resolution in axis Z

On the plane parallel to the sensor plane, resolution  $\Delta X$  in axis X is then determined based on the dimensions of the field of view and sensor resolution given in pixels. Resolution  $\Delta Y$  in axis Y is defined as the distance between the acquisition of an image of the successive height profiles of the test object. When calculating the resolution in the configuration presented, an approximation is used where we assume that angle  $\alpha$  is equal to angle  $\alpha_1$ . In fact, angle  $\alpha_1$  is equal to:

$$\alpha_1 = \alpha - \gamma \quad (2)$$

However, when determining resolution based on the formula below, the following is assumed for calculation purposes:  $\alpha_1 = \alpha$ . As a result, such a simplification does not significantly affect the outcome of resolution in axis Z.

$$\Delta Z \approx \Delta X / \sin(\alpha) \quad (3)$$

where:  $\Delta Z$  – resolution in axis Z,  $\Delta X$  – resolution in axis X,  $\alpha$  – the angle between the axis of symmetry of the laser and the optical axis of the camera.

Resolution in axis X and axis Z is determined in millimetres per pixel. If sub-pixels image processing is to be conducted, then the value calculated per pixel should be divided by the value of pixel division coefficient. Then, it is possible to determine movement of the line on a screen with the resolution of e.g.  $\frac{1}{2}$  pixel,  $\frac{1}{4}$  pixel or any other. Using a 1536x512 pixel sensor and a lens for the vision system allowing observation of a 64 mm wide object (FOV = 64mm), resolution in axis X and Z was determined for the test object.

$$\Delta X = 64\text{mm} / 1536\text{pixels} = 0.041[\text{mm} / \text{pixel}] \quad (4)$$

$$\Delta Z \approx 0.041 / \sin(45^\circ) = 0.058[\text{mm} / \text{pixel}] \quad (5)$$

On the plane parallel to the plane of the sensor, with the resolution  $\Delta X$  in axis X known, resolution in the axis perpendicular to X is also taken to be  $\Delta X$ . Resolution in axis Y of the coordinate system is dependent on the shift of the table between the successive image acquisitions by the vision system. Assuming that in the

object displacement measurement system there is an encoder sending 1600 pulses per 1 mm of table displacement for an image acquired every 160 pulses, resolution in the direction of axis Y is

$$\Delta Y = 160[\text{imp} / \text{scan}] / 1600[\text{imp} / \text{mm}] = 0,1[\text{mm} / \text{scan}] \quad (6)$$

A three-dimensional image of the object is built from profiles collected during object movement in the direction of axis Y of the test station. The vision system captures a profile image each time after the object moves by 0.1 [mm], i.e. 160 pulses. In axis X, the resolution is 0.041 [mm] and it is the distance between successive measuring points on that axis without sub-pixel processing. Resolution in axis Z is equal to 0.058 [mm]. In case of sub-pixel image processing, the resolution in axis X and Z takes into account the coefficient resulting from the pixel division algorithm.

After acquiring the image, a procedure is carried out to translate the laser line visible on the sensor into profile height in each of sensor column. The most important element of this analysis is precise definition of the position of the centre of the laser line as seen by the vision system. Each column of the image is presented as a function of intensity  $f(x)$ , where the argument is the number of a pixel in the column. Then, for each column, the position of laser line centre is determined, and thus complete information about line position needed to calculate the height of the profile point is obtained. For each sensor column (Fig. 8b), a value of the change in intensity along the pixels forming the column is determined (Fig. 8a). Then, the centre of the laser line is determined.

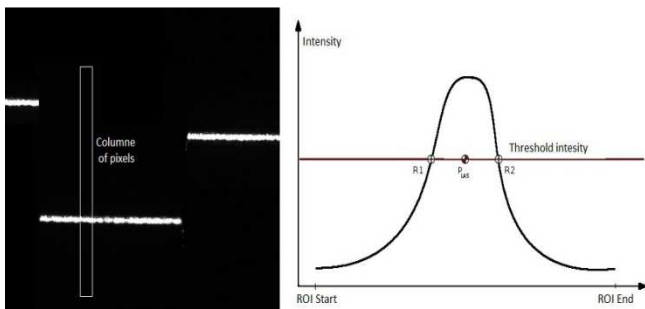


Fig. 8. Algorithm to determine the position of laser line in the successive sensor columns

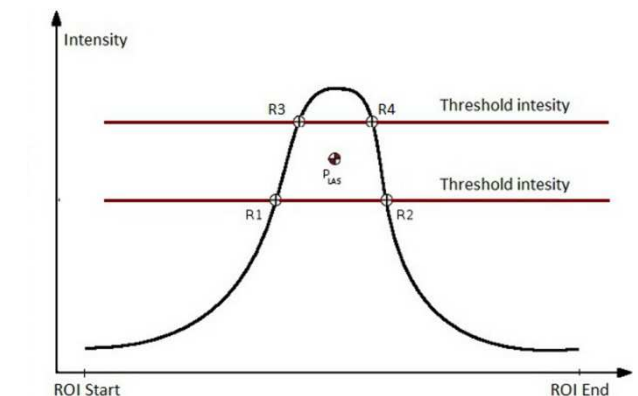


Fig. 9. Determination of laser line centre using double intensity threshold

To determine the centre of the laser line, the method of threshold intensity definition is used. In that method, an intensity threshold defined by the user is put in. If there is no interference and the threshold was well chosen, it intersects the intensity diagram at two points (R1 and R2). The centre of the laser line

is determined as the arithmetic mean of pixel positions where the diagram intersected with the threshold. Analysis of intensity in a column, using an intensity threshold, allows obtaining resolution of  $\frac{1}{2}$  pixel. In order to increase the resolution of laser line centre determination, two intensity thresholds should be used. In such case, four points describing the intensity function are available and laser line centre is determined as the arithmetic mean of the positions of those points. The use of two intensity thresholds allows obtaining resolution of  $\frac{1}{4}$  pixel (Fig. 9).

$$x_{LAS} = \frac{x_{R1} + x_{R2} + x_{R3} + x_{R4}}{4} \quad (1)$$

### 3. OBJECT MEASUREMENTS ON 3D IMAGE

The vision system observes an image of the given piece in the manner shown in Fig. 10a. Parameters of the vision system are chosen in such a way that the image shows only a trace of the laser line. It is also important that in the event of accidental reflection of laser light from other surfaces of the object, the trace of that reflection is not visible on the image. The impression of the tested object is removed from the image. Based on the sequence of images collected, height profiles of the tested object are determined in the successive cross-sections. Figs. 10a and 10b show an image and a profile of an incorrect edge. Fig. 10c shows a profile of a correct edge.

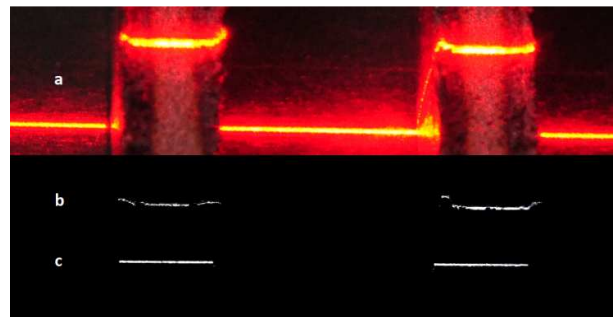


Fig. 10. Laser beam illuminating the object

On the basis of the prepared height profiles that form the successive cross-sections, a three-dimensional image of the object is constructed. View of a piece with correct cutting edges is presented in Fig. 11a. Fig. 11b shows edges with visible cutting defects (burr).

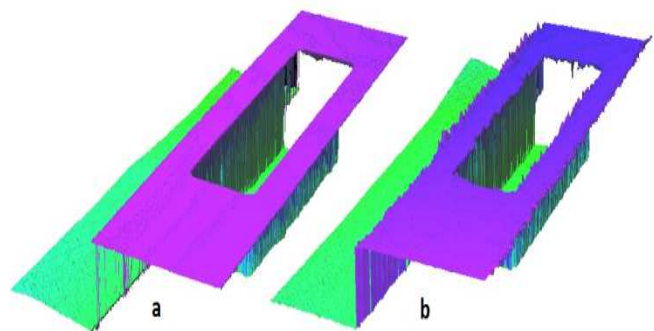


Fig. 11. 3D image of a product:  
 a – correct, b – with defects on cutting edges

Both in the case of the profile and the 3D image, there are distortions of the image resulting from both the geometry of the system as well as from the laser light reflected from the surface of the object. As a result of occlusion, the three-dimensional image does not show the portions of the object which the laser light does not reach. Such an image must be filtered prior to the implementation of a control procedure. Fig. 12 shows an image after smoothing filtering using a structural element – a 3x3 sensor. However, it should be noted that in the course of smoothing, the height of “peaks” appearing in the image will have an impact on the value of points in their vicinity.

After performing image transformations, as a result of which noise is removed from the image, an analysis of the quality of cutting may be performed for a selected edge of the object. That analysis should be performed using assessment of the height profile along the tested edge of the object (Fig. 12).

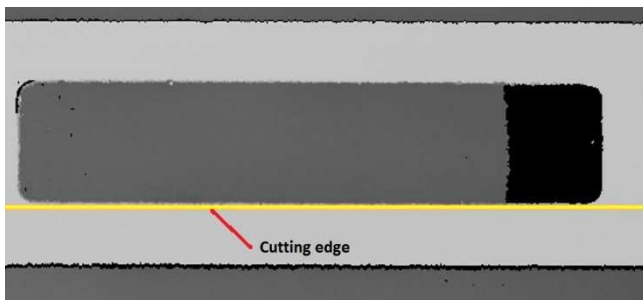


Fig. 12. An edge along which the height profile has been determined

For the tested profile, a comparative analysis was carried out of the height of unevenness in a correct edge and in an edge with a visible defect. The incorrect edge and its three-dimensional image are shown in Fig. 5 and 11b respectively.

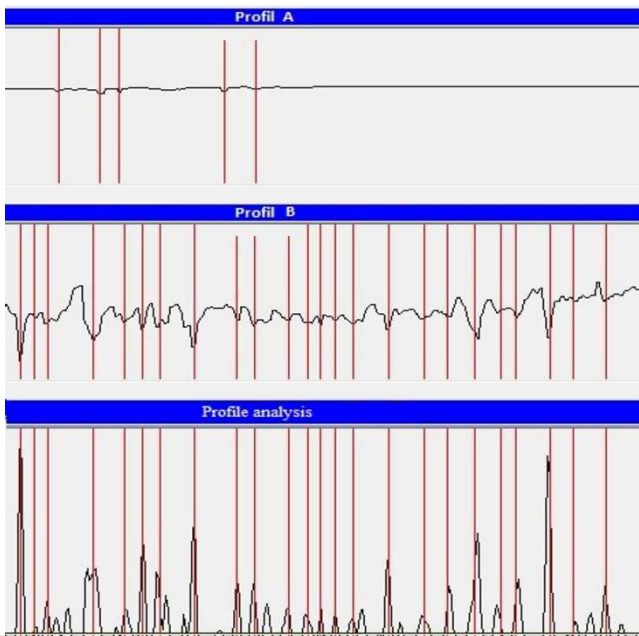


Fig. 13. Measurement of edge defect

A height profile of a proper edge is described in Fig. 13 as “Profile A”. Small interferences (chipping) can be seen marked with 5 vertical lines. Quality of the edge was assessed by measur-

ing the deviation of the height of the cutting edge from the nominal profile. The nominal profile is determined based on an assessment of the height of the surface of the material outside the cutting edge.

A defective cutting edge is described as “Profile B” (Fig. 13). The height of profile unevenness shows visible distortions in relation to the proper edge. The values of such deviations from the nominal profile at selected points described for an incorrect edges are shown in the bottom part of Fig. 13 and are identified as “Height of profile unevenness”. Those heights are determined at the resolution specified in this paper. Based on such information, the algorithm implemented into the video system enables measurement and assessment of the product on selected edges and planes.

Another method of measuring edge defects is the assessment of edge shape in relation to a reference plane. The reference plane was determined on the basis of analysis of points spaced around the edge of the object (Fig. 14). The figure shows a three-dimensional image of edges above the reference plane. During the research, the volume of edges was measured in relation to the plane and were thus a quantitative parameter describing the defective edge was obtained. In the case of proper edges, the volume should be close to zero.

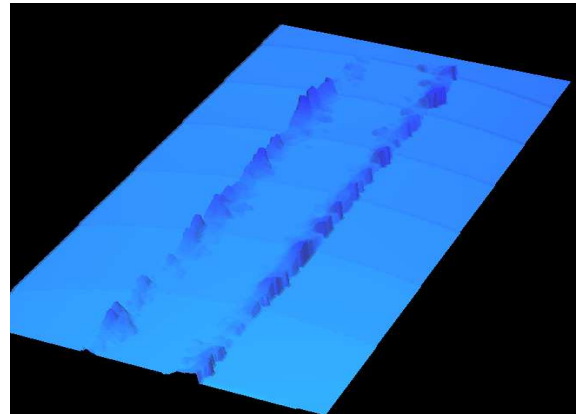


Fig. 14. Measuring the volume of material visible above the reference plane

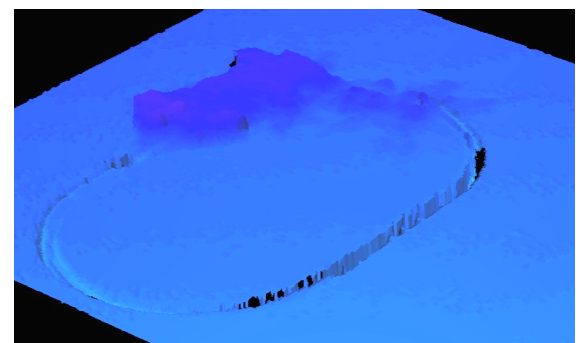


Fig. 15. Measuring the volume of material visible above the reference plane

Similar algorithms were also applied to the assessment of defects described in the first part of the paper. Profile height measurements combined with volume measurements and hole dimension measurements allow unambiguous assessment of the presence of a hole and its defects. Figure 15 shows an incorrect hole from which material has not been removed.

#### 4. SUMMARY

In the course of research, algorithms for the detection and assessment of defects generated during laser cutting were developed. Those algorithms, developed and tested on products, confirmed the effectiveness of the vision method for assessing defects. A significant advantage of the solution is the possibility of controlling the product on all edges and surfaces simultaneously within about 1 s. That enables precise control of all products leaving the production line. As a result of the analysis, identifying presence of the material in an opening and presence of burr on the cutting edge was made possible. Also, detection of a defect in a three-dimensional image of the product makes it possible to send feedback information to both the operator of the technological line and to the machine control system. It is crucial information that prevent the manufacturing of defects in the process.

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