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Detection of Straightness Deviation on a Production Machine in an Automatic Cycle

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Abstract: The article presents a method of measuring straightness of a metal flat bar on a production machine in an automatic cycle. The measurement was carried out while the production machine was operating, using a laser profilometer. In order to determine straightness, the measurement results were used along the entire length, the maximum deviation was calculated and presented, defining whether the measured part meets production requirements.

Keywords: straightness deviation; algorithm; measurement; laser profilometer

1. Introduction

The Japanese concept of Lean Management is very popular all over the world. More and more production plants implement its assumptions and use the tools it offers. One of the basic methods used in this area is Just In Time, which aims to minimize breaks between subsequent stages of production and reduce warehouse stocks, i.e. producing exactly as much as the customer requires. At the same time, this should be done in the shortest possible time and with the smallest possible losses incurred during this production. In the era of widely available tools and devices, production time and product quality are crucial when choosing a supplier. In order to maintain appropriate quality, control measurements are introduced during production. Performing these measurements is an additional burden for production workers, whose main goal is to produce in accordance to the established quantity standard. Often, the need to produce a given batch within a specific time may result in placing quantity over quality. That is why companies try to automate measurement processes to detect nonconformities and defects at the earliest possible stage of production, while minimizing costs. Due to the number of necessary measurements, automation also relieves employees of this task [1, 2].

According to that, the main reason for the research was to develop a method for measuring the straightness of metal profiles on a specific machine during the automatic cycle, without a negative impact on the cycle time. Before installing the measuring system on this machine, the straightness of the profiles after the straightening process was checked manually by a company employee on a table dedicated for this purpose.

1.1. Straightness tolerance

Straightness tolerance is the measurement of the deviation of a measured straight line from a geometrically ideal straight line. Straightness deviation is the greatest distance between a real straight line and an adjacent straight line or the greatest distance between a real plane and a straight line adjacent to it in a given direction. The boundary of the tolerance zone is formed by two parallel lines at a distance t, resulting from the permissible tolerance value of this deviation. An illustration of the above definitions is presented in Figure 1 [3, 4].

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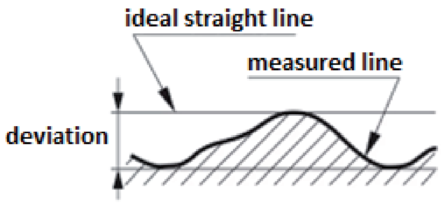

Figure 1: Linearity deviation [4].

1.2. Laser profilometer

A laser profilometer is a measuring device that generates a line-shaped laser beam, the reflected light of which is captured by a photosensitive matrix. The measurement is obtained based on the principle of laser triangulation, i.e. calculating the position and distance of the measured shape in the X and Z axes. An example of a laser profilometer is shown in Figure 2. This allows for the creation of a 2D profile of the tested object, which can be used to determine the height, width or angle of the tested detail. The diagram of the operation of the discussed system is shown in Figure 3. According to the technical documentation of the device, one of the advantages of these sensors is the measurement of straightness across the entire width of the beam [5, 6].

Figure 2: 2D/3D Laser profilometer MLSL123 [5].

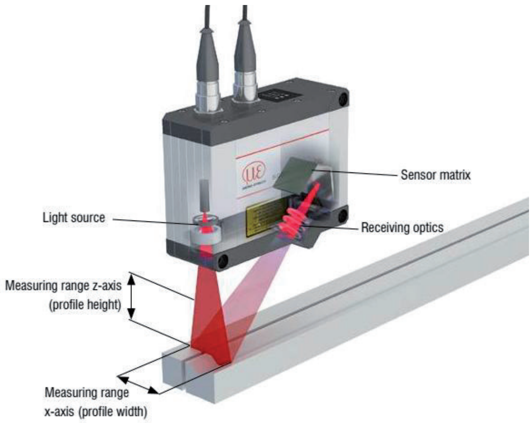

Figure 3: Diagram of the operating principle of a laser profilometer [6].

In the application presented in the next subsection, the MLSL123 laser profilometer from Wenglor was used. Its main advantage is the possibility of measuring in two axes. It is characterized by a linear deviation of 95 µm over the entire measuring range, which is 190 mm for the Z axis and 62-145 mm for the X axis. The operating range of the sensor in the case of a device from the MLSL1x3 series is shown in Figure 4 [7].

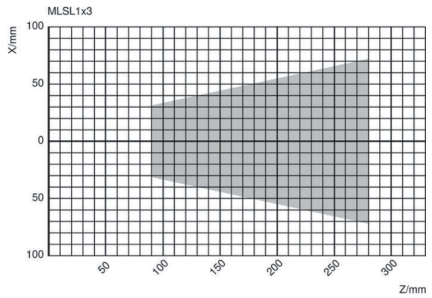

Figure 4: Measuring range of the MLSL123 laser profilometer [7].

2. Experimental Section

The research was carried out on a machine used for straightening steel profiles. The operation of the machine consists in separation of one profile (flat bar) from the batch placed on transport chains, positioning it and subjecting it to the straightening process. Next, the straightened flat bar is moving to the measurement area and measuring of the shape in two axes at a given point starts. Measurement is done using a laser profilometer [3] moving on an additional axis along the entire length of the flat bar. After measuring the profile is transported to unloading zone. During measurement, the profile is transported to specially prepared prisms that position it along its entire length. Then, by simultaneously rotating the prisms, the flat bar is set at a given angle so that the laser beam can measure it in two axes through the measurement holes. The dimensional range of flat bars that can be processed at the station is 3000-6000 mm in length, 16-200 mm in width, 5-30 mm in thickness. The machine elements responsible for measuring straightness are presented in Figures 5 and 6.

Important issue is measurement uncertainty during this measurement. The MLSL123 profilometer used in the experiment has a declared linearity error of ±95 µm across its full measuring range (Z-axis: 190 mm, X-axis: 62–145 mm), according to the

Figure 5: Photo of a fragment of a machine positioning a flat bar for measuring straightness.

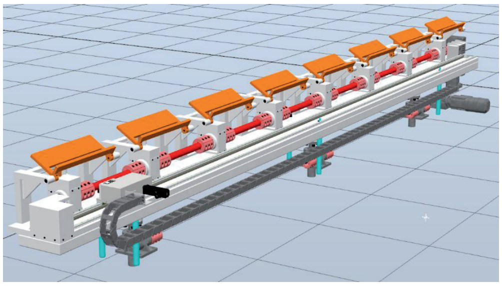

Figure 6: 3D model of the measurement system.

manufacturer's specifications [7]. However, during measurement there were taken additional factors which can affect measuring uncertainty:

- *Surface reflectivity and toughness,*
- *Vibrations of machine components during operations,*
- *Angular misalignment between the profilometer and the flat bar,*
- *Mechanical deviations of the moving carriage with profilometer.*

Any measurements which were significantly different from expected were ignored, according to known quality and shape of flat bars.

While traveling along the edge of the flat bar, the profilometer is covered by transport chains placed every 0.9 m and by measuring prisms responsible for the orientation of the detail. These elements significantly influence the arrangement of the detail. The plastic deformation that affects the straightness of the flat bar changes with the rotation of the detail. The smallest deformation occurs when the longer wall of the flat bar is perpendicular to the ground. However, in such a case, without proper support, the detail could tip over. The same effect may occur when the dynamics of the ramp movement responsible for the rotation of the detail is too high.

To sum up, in an ideal measurement position, process automation is difficult to implement. On the other hand, with the normal orientation of the flat bar (longer wall parallel to the ground), plastic deformation caused by gravity may distort the measurement. The same will happen if the detail has too much support when rotated. Reducing the number of supports may again cause the detail to give under its own weight. Analysing the above conditions and based on the preliminary tests, the 60° angle turned out to be the best value. Of course, it is not possible to completely eliminate the influence of gravity and support friction, which may affect the results. However, this angle is sufficient to enable automation of the process. Figure 7 shows the positioned flat bar and the forces acting on it. The forces marked Fz and Fx are the plastic deformation of the material in a given axis. The vector Fg, on the other hand, means the gravitational force.

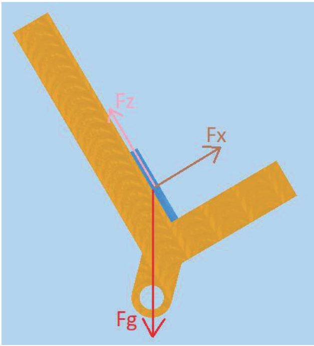

Figure 7: Force vectors influencing flat bar during measurement.

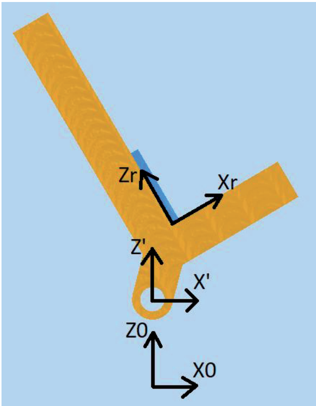

Figure 8: Designated coordinate frames during measurement.

The tested flat bar is located at an angle to the coordinate system of the measuring device, so the displacement of the edges on this plane is the sum of the unevenness of both walls of the flat bar (width and thickness). This problem can be solved using the transformation matrices. For this purpose, three coordinate systems have been introduced in Figure 8:

- *X0Z0 – measuring device system,*
- *XrZr – flat bar rotation system,*
- *X'Z' – flat bar arrangement.*

The rotation system of XrZr is shifted relative to the measurement system, which should be taken into account first using the translation matrix (1). The next step is to take into account the rotation of the measurement system. In this way, equation (2) will be created, from which it is possible to determine equations (3) and (4) that determine the actual position of the tested corner point in the XZ plane [8].

$$\begin{bmatrix} \cos\beta & 0 & -\sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ \sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\beta & 0 & -\sin\beta & x \\ 0 & 1 & 0 & y \\ \sin\beta & 0 & \cos\beta & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$x = cos\beta \cdot a + 0 \cdot b + \left(-sin\beta\right) \cdot c = a \cdot cos\beta - c \cdot sin\beta \quad (2)$$

$$y = 0 \cdot a + 1 \cdot b + 0 \cdot c = b \quad (3)$$

$$z = sin\beta \cdot a + 0 \cdot b + cos\beta \cdot c = a \cdot cos\beta + c \cdot cos\beta \quad (4)$$

3. Results and Discussion

The measuring device allows to read the current values of points on the XZ plane. In the case of the tested flat bar, after taking into account equations (2) and (3), these points determine the position of the edges, while the Y axis is responsible for the absolute position of the measurement system. Figure 9 shows the measurement result in the XY plane after taking into account the orientation of the flat bar.

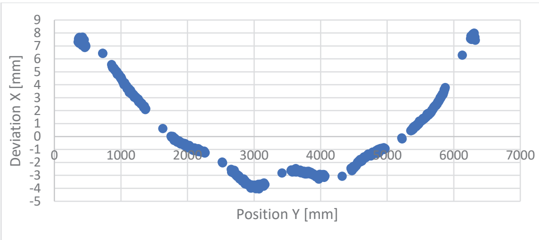

Figure 9: Obtained edge positions in the XY plane.

Analysing Figure 9, you can notice visible breaks in the measurements. They result from the previously mentioned need to support the flat bar and from the transport chains covering the detail. Another aspect is the parabolic shape of the graph, which could indicate the lack of straightness of the element. If the measurement result refers to the absolute values of the entire flat bar, the deviation is less than 12 mm (-4.04 - 7.65 mm). A different approach should be taken when straightness is tested on a given section. For example, on the section 2600 - 3600 mm (Figure 9) the deviation was 1.4 mm, while for the section 400 - 1400 mm it was as much as 5 mm (2.05 - 7.22 mm). These values represent the corner positions in the XY plane. Straightness determines the way in which individual points are distributed on a given section.

To sum up, when verifying sectional straightness, another operation is necessary: for each measurement point (point A), another point is determined that is a set value away (point B), and the maximum deviation is determined by the distance of the points from the straight-line connecting points A and B. Using the diagram in Figure 10 for the example in Figure 9, point A will be 400mm (X = 2.05mm) and point B will be 1400mm (X = 7.22mm). The line connecting these two points corresponds to a deviation of 0mm. By performing one iteration of the algorithm from Figure 10 for the given values of A and B, we will obtain a maximum deviation of 0.88 mm at position 728 mm.

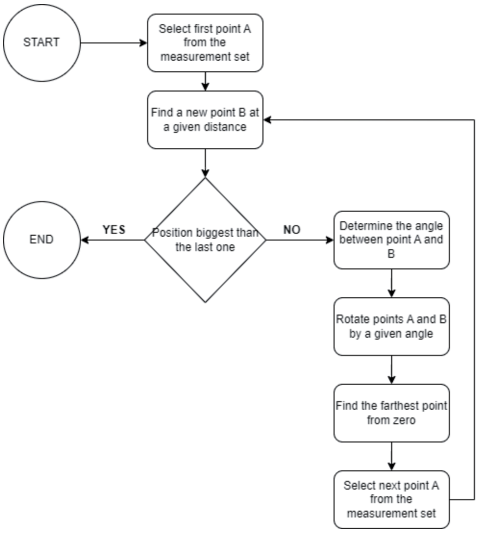

Figure 10: Diagram of the procedure for determining subsequent deviations.

The methodology presented in Figure 10 allows for determining the maximum deviation for subsequent points. The effect of such an algorithm is presented in Figure 11, which shows the actual deviation in relation to the obtained measurement. As you can see, the deviation for the value of 728 mm was ultimately 1.01 mm, because this point was further away for the section 371 - 1370 mm.

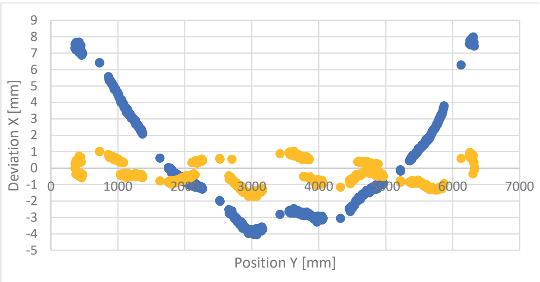

Figure 11: Obtained edge positions in the XY plane taking into account the actual deviation.

In order to achieve full automation of the measurement, it is necessary to draw a tolerance line of ±1 mm/1 m (for a tolerance of ±2 mm/1 m, the detail would obtain the OK status, even though initially, due to its shape, it showed a horizontal deviation of ±8 mm). A similar procedure was performed for the YZ plane, as shown in Figure 12.

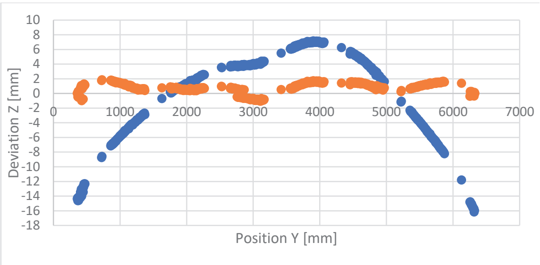

Figure 12: Obtained corner position in the YZ plane taking into account the actual deviation

The largest deviation for the presented flat bar was:

– *1.73mm for position 3028mm relative to points 2520-2620mm on the XY plane,*

– *1.87mm for position 728mm relative to points 376-1376mm on the YZ plane.*

4. Conclusions

In order to verify the repeatability of the measurement, tests were carried out, during which it was found that the maximum measurement error was less than 0.1 mm, which is an order of magnitude smaller than the assumed measurement tolerance. For this reason, this system can be used in an industrial solution ensuring the correctness of the measurement. The use of a laser profilometer presented in the article confirms that with appropriate implementation of the sensor and data processing, using elementary operations on numbers and matrices, an advanced measuring device can be implemented into the production process. The use of machine positioners, which set the profiles at a given angle before the measurement, and the rotation matrix made it possible to perform a measurement reflecting the actual condition. The ability to control the straightness of profiles during series production allows for real-time supervision of the process. It minimizes losses by detecting a deviation in the straightness dimension that exceeds the permissible tolerance, and thus reduces the risk of sending goods to the customer that do not meet the requirements. Automation of the process of feeding flat bars for straightening, measurement and storage allowed a reduction in the number of employees. This would not be possible without a measuring device that would direct the flat bar to the appropriate OK/NOK warehouse. Integrating the measuring system with the machine also makes it possible to archive the measurement results obtained for a given batch of elements. In line with continuous improvement, a potential next modification may be, for example, equipping the station with a detail marking system that will enable the implementation of the Traceability system, i.e. tracking the product and its parameters throughout the process.

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