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Research on Accuracy of Automatic System for Casting Measuring

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Abstract

Ensuring the required quality of castings is an important part of the production process. The quality control should be carried out in a fast and accurate way. These requirements can be met by the use of an optical measuring system installed on the arm of an industrial robot. In the article a methodology for assessing the quality of robotic measurement system to control certain feature of the casting, based on the analysis of repeatability and reproducibility is presented. It was shown that industrial robots equipped with optical measuring systems have the accuracy allowing their use in the process of dimensional control of castings manufactured by lost-wax process, permanent-mould casting, and pressure die-casting.

Keywords: Automation and robotics in foundry, Product development, Mechanization and automation of casting processes, Quality control of castings, Ability of the measurement system

1. Introduction

The foundry companies as well as their customers need to perform quality control to guarantee the required specifications. The simplest and most common method of castings control is the manual method that consists in the accurate measurements and assessment of the results by qualified staff. For this purpose, the simple measuring devices, such as calipers, micrometers and reference standards are used for comparative control (templets). The assessment of the casting state also depends on a visual assessment of the correctness of manufactured element [1-5]. Manual methods are very simple and cheap. Their main disadvantage is the long realization time, and it is connected with a small efficiency. The disadvantage of the manual method is also a greater probability of errors in comparison with the automated methods used for evaluation of the casting quality. Automation of measurements usually involves the use of a coordinate measuring machine (CMM) or optical measuring devices [6]. CMM's allows to perform spatial measurements (3D) of geometrically complex elements. The most common CMM is equipped with three measurement systems to measure in three axes XYZ and the probe for the localization of the position of the element surface. Thanks to drives with high accuracy and computerizing control system, it is possible to make measurements relatively fast with very high accuracy and objectivity.

Particularly complex part geometries with inaccessible or hidden features can be also measured with X-ray computed tomography (CT). Complete 3D mapping means that CT can also be used for the non-destructive 3D measurement of cast parts that cannot be inspected using conventional coordinate measuring machines due to their complex internal geometry [7]. With industrial X-ray computed tomography (CT), even low-contrast defects in cast parts, such as cracks, pores and blowholes, can be localized and measured in three dimensions [7]. Since both material and geometry data can be retrieved from the measurement, the results can be used for the detection of defects as well as for the investigation of geometrical and material variations [8].

The coordinate measuring technique is based on the values of the coordinate measurement points. All feeds that the contact tip of measuring device makes are recorded by the side-guiders. As a result, every motion is recorded on the server of the machine and it is transmitted to the computer. The spherical tip by contact with the measured object records the points in the system. Based on points registered by the CMM we can reconstruct many kinds of flat geometric elements (points, circles, planes, straights, curves) and the spatial geometric elements (fight, cones, spheres).

The great advantage of using the CMM is performing the measurements of various objects with complex shapes that cannot be measured with the use of basic measuring instruments. However, for castings as a semi-finished product, the use of the CMM is inadequate, considering the high cost and the required precision of the measurement level (50-400 μm) [9]. An alternative solution, that offers similar functionality is an optical measuring system installed on the arm of an industrial robot. Robots are characterized by the increased speed of movement of the arm (to 0.5 m/s) in relation to the CMMs. They can also move with several times greater acceleration (up to 4 m/s), that significantly increases the efficiency of measurement system. The standard robotic measuring position consists of [9]:

- bearing assembly that provides the ability to move the measuring head in the axes Z, Y and Z,
- optical scanner,
- computer containing the software for processing the measurements results.

Optical measurement method is based on the projection of the light with known structure (white or blue) on the examined object. The measurement involved CCD cameras and a projector (light source). A number of different structures of light that differs in density is projected on the surface of the investigated object during scanning. The most important action during the optical method based on structured light projection realization is properly carried out calibration of the cameras and the projector. It is also important structure of the object under test. The accuracy of the optical method also depends on the structure of the investigated object. The reflective surfaces are very problematic, because they do not provide an adequate contrast of the fringes projected by the projector. The accuracy of the scanners that use structured light depends on the measuring range and varies between 0.01 and 0.1 mm. The collected point cloud is processed by the appropriate software that generates a virtual representation of the surface for dimensional analysis [10-14].

The accuracy of robotic measuring positions must meet certain requirements in order to ensure the economic price of the casting. The relationship between measurement uncertainty and tolerance of the controlled feature is the indicator of the usefulness of the measurement system (measuring ability of the system) [15, 16]. In industrial plants, especially in the automotive industry, the criterion of suitability is formulated based on the analysis of repeatability and reproducibility (R&R) of results of measurements. This method has been developed by companies: Ford, Chrysler and General Motors, and implemented in the form of the requirements of the quality system according to the QS-9000 standard [17]. After appropriate modifications, it can also be used to assess the ability of the robotic measurement system. Therefore, a further part of this work has been devoted to this issue.

2. Characteristics of investigated measuring systems

Investigations of the accuracy of measurement systems were carried out for the experimental part, in the same environmental conditions and with the use of the same method of building a measurement coordinate system. The measurements were performed using two measurement systems:

- CNC Mitutoyo CRYSTA-Apex S coordinate measuring machine designed for measurements of geometric dimensions of machine parts in a manual and automatic cycle (Fig. 1),
- robotic measuring position consisting of Fanuc M-10iA industrial robot equipped with the GOM Atos Triple Scan head (Fig. 2).

Fig. 1. High-accuracy CNC coordinate measuring machine CRYSTA-Apex S

Fig. 2. Industrial robot with optical measuring system GOM Atos Triple Scan

The M-10iA is FANUC Robotics' latest-generation, six-axis, high performance industrial robot. This small but mighty robot weighs only 130 kg but provides 10 kg payload with the highest wrist moments and inertia in its class. ATOS Triple Scan uses all the viewing angles of the stereo camera system (3-in-1 sensor). It is also based for the very first time on a completely new projection technology. Therefore, the scanner enables easier, faster and more reliable measurement processes and greatly reduces a number of single scans. The measurement accuracy of ATOS system is lower than 0.03 mm for the measuring range of 700x700 mm. The accuracy, measurement resolution and measuring area are completely adaptable to the application requirements. This allows for the highest resolution for highly detailed, small parts with measuring volumes down to 38 mm, or for extremely fast digitizing of large objects with measuring volumes up to 2m.

The ATOS sensor is freely positioned, either manually or automatically, in front of the part. After each measurement, the sensor or the part is moved to obtain areas not captured in the previous scan [11]. The stereo cameras combine with the projector to capture three views of an object in a single measurement process. This technology requires fewer scans and delivers higher quality data even when scanning shiny surfaces and complex geometries (Fig. 3). All individual measurements are automatically transformed into a common coordinate system resulting in a complete 3D point cloud.

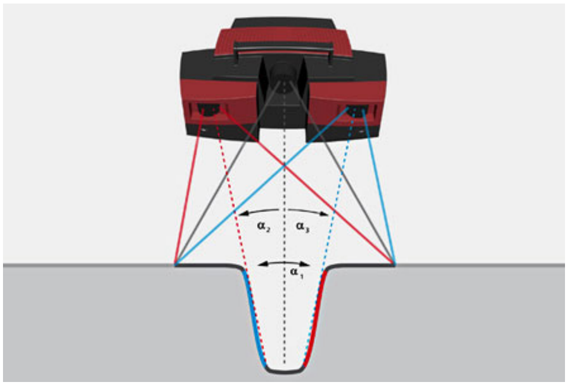

Fig. 3. The schematic of the scanning using GOM Atos Triple Scan head [11]

3. Research on measurement systems accuracy

The aim of measurements was to control the quality of the selected element. The following parameters were checked:

- a diameter of through holes,
- diameters of blind holes on the upper surfaces of the element,
- linear dimensions,
- the flatness of the selected surface of the element,
- roundness errors measured at four hole heights (h = 8-20 mm).

Measurements on the scanner and the coordinate measuring machine were repeated 5 times and then both the mean value and standard deviation were determined. The results of measurements of linear dimensions are shown in Table 1.While the results of measurements of the surface flatness and the hole roundness are presented in Table 2. The results of measurements of the surface flatness were evaluated based on measure of three selected points on the analyzed surface and based on the measurement of points on the whole surface. The second type of the surface measurement is possible only using the optical scanner.

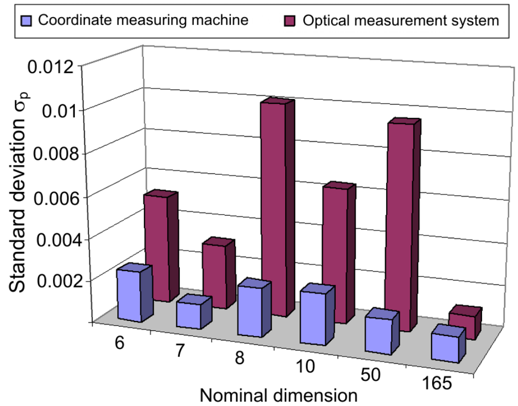

Fig. 4. The values of standard deviation of measurement repeatability error

To assess the ability of the measurement system the potential sources of measurement uncertainty in the context of the components of the measurement should be analyzed. If the real value of the measured parameter is denoted by x_p, the measurement result will depend on both repeatability and reproducibility errors, according to the formula:

$$W = x_p + \Delta_p x + \Delta_o x \tag{1}$$

where: Δ_{ox} – reproducibility error of a measurement
Δ_{px} – repeatability error of a measuring machine

The first component of the measurement uncertainty is a component resulted from both dispersion of indications of a measuring instrument, and dispersion of the observed indicators during the measurement realization. The measure of the measurement uncertainity is the experimental standard deviation σ_p determined based on the series of measurements (Fig. 4):

The analysis of measurement results listed in Tables 1 and 2 shows that the repeatability error of the optical system is connected with a much larger error value. This value is greater than the error generated by the CMM from 8% to as much as 500% (Table 1). A similar situation is in the case of measuring the surface flatness (253%) and the roundness of the hole (530%). However, in the case of measurement of the surface flatness the repeatability error of the optical system can be reduced by changing the method of the measurement. The measurement that takes into account the points on the whole scanned surface reduces the error at 33%.

Table 1.
Results of measurements of linear dimensions

Nominal dimension x_p, mm	Optical measurement system		Coordinate measuring machine	
	Average value x_{av}^m, mm	Standard deviation σ_p, mm	Average value x_{av}^s, mm	Standard deviation σ_p, mm
6	5.9846	0.0052	5.9948	0.0024
7	6.9809	0.0031	6.9874	0.0012
8	8.0078	0.0101	8.0051	0.0023
10	10.1485	0.0064	10.0037	0.0024
50	50.016	0.0096	50.0028	0.0016
165	164.9221	0.0011	164.9907	0.0012

Tabela 2.
Results of measurements of surface flatness and hole roundness

Parameter		Optical measurement system		Coordinate measuring machine	
		Average value x_{av}^m, mm	Standard deviation σ_p, mm	Average value x_{av}^s, mm	Standard deviation σ_p, mm
Surface flatness (three points)		0.0947	0.0012	0.0982	0.00034
Surface flatness (the whole surface)		0.1210	0.0008	-	-
Roundness error	h = 8mm	0.0454	0.00049	0.0403	0.00020
	h = 12mm	0.0476	0.00048	0.0432	0.00032
	h = 16mm	0.0425	0.00095	0.0423	0.00006
	h = 20mm	0.0533	0.00293	0.0631	0.00019

Assessment of the accuracy of the measurement system also needs to take into account the reproducibility. Reproducibility of a method/test can be defined as the closeness of the agreement between independent results obtained with the same method on the identical subject (or object, or test material) but under different conditions (different observers, laboratories, machines, etc.) [18].

Figure 5 shows the difference between the average values of results of measurements obtained using the coordinate measuring machine x_{av}^m, and using the optical scanner x_{av}^s.

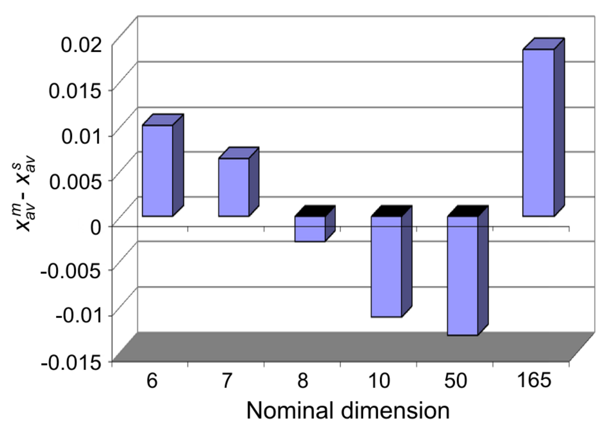

Fig. 5. The differences between the average values of measurements obtained using both the coordinate measuring machine x_{av}^m and the optical scanner x_{av}^s

In the case of assessing the accuracy of the automatic measurement systems on the reproducibility depends on a method of measurement. The difference in the average values of measurements obtained using both the coordinate measuring machine and optical scanner varies from -1.32% to 1.86%.

If we assume that the results of measurements obtained on the CMMs as model results, then it turns out that the optical scanner is burdened with an additional reproducibility error causing the change of mean values obtained by CMM. But this is not a systematic error because there are no linear correlation between the obtained mean values. Therefore, it should be assumed that the value of reproducibility error is a random variable. Based on the results of investigations we can only estimate the range R of obtained results (R = 0.032 mm). On the basis of the Eq. (2) we can estimate the value of the standard deviation of the random variable representing simultaneously an estimator of the reproducibility error of the optical system σ_o (0.0053mm) [19]:

$$\sigma_o = \frac{R}{d_n} \tag{2}$$

where d_n – Hartley's constant.

In the course of assessing the accuracy of the measurement system error variance σ^2 of the total will be the result of variance characterized reproducibility: measuring instrument σ_p^2 and variance σ^2 characterized reproducibility (Fig. 6):

$$\sigma^2 = \sigma_p^2 + \sigma_o^2 \tag{3}$$

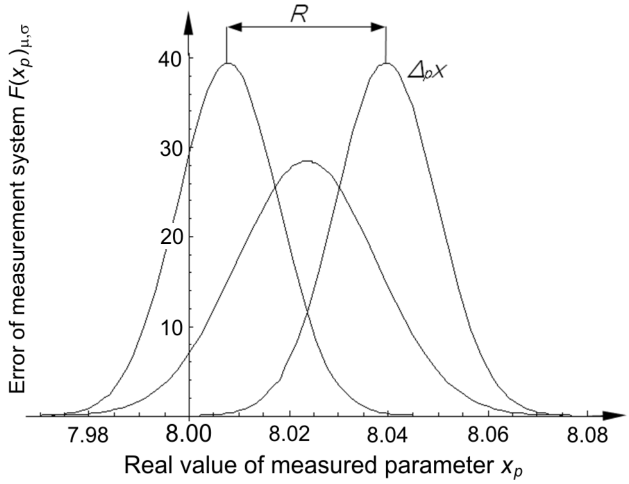

Fig. 6. Interpretation of the total error of the measurement system

Because the value of the repeatability error of the optical system has changed over a very wide range, so for further analysis we assumed the highest observed value of σ_p = 0.0113 mm. According to QS-9000 standard distribution range is determined on the confidence level of 1-α = 0.99, according to the Eq. 3 [17]:

$$R_{0.99} = 2k_{0.99}\sigma = 2 \cdot 2{,}575\sigma = 5.15\sigma \quad (3)$$

therefore, repeatability and reproducibility (*R&R*), as a derivative of σ_p^2 and σ_o^2 is equal to:

$$R\,\&\,R = 5.15\sqrt{\sigma_p^2 + \sigma_o^2} \quad (4)$$

As an indicator of the measuring ability of the automatic measuring system to control certain feature of the casting we can assume the relationship between the value of *R&R* and the feature tolerance. If the ratio of $R\&R/T \leq 10\%$ it should be assumed that the measuring system is qualitatively capable when the value of mentioned relation is between $10\% < R\&R/T \leq 30\%$. In this case the system is suitable for the control of secondary measurements, while in the other case the system is characterized by too large error to apply it to the measurement of the parameter in the specified tolerance.
The analysis showed that the optical measurement system can be used to measure the casting with following tolerances:

– for the measurement of linear dimensions: not less than 0.195 mm,
– for surface flatness measurement: not less than 0.026 mm,
– for roundness measurement: not less than between 0.07 mm.

The presented requirements correspond to the economic dimensional tolerances of castings with the dimension of 10-50 mm performed by lost-wax process (0.06-0.2 mm), by the Shaw method (0.2-0.6 mm) by a permanent-mould casting (0.2-0.6 mm) and by a pressure die casting (0.1-0.4 mm) [20].

4. Conclusions

During the control of quality of casting process the finished cast is evaluated and compared with the requirements concerned on dimensions and structural defects, and surface quality. Depending on the type and the size of the cast and the casting quality control of the cast can be realized visually, using measuring machines, or may take place in an automatic cycle. Currently, the most popular and most commonly used method of control the casting is the manual method using appropriate master templets. This method is cheap but it is time-consuming and inflexible. In this article, it was shown, that the quality control of castings may be realized using an optical measurement system. This system is less precise than the coordinate measuring machine, but accurate enough to measure castings produced by lost-wax process. A considerable advantage of the optical system is non-contact measurement method that allows its use at the design stage of the model. It allows to identify discrepancies at an early stage of the manufacturing process. Furthermore, the robotic stand provides great flexibility of the measurement. Thanks to multiaxiality of the robot arm the measuring position becomes more universal, and the robot can be used for many tasks.

References

[1] Zator, S., Gasz, R. (2013). Methods of using image analysis to control the quality of castings. In 16th Conference on Innovations in Management and Production Engineering, 24-26 February 2013 (pp. 1023-1033). Zakopane, Polska.
[2] Zdanowicz, R. (2003). *Automation of Technological Processes*. Gliwice: Wydawnictwo Politechniki Śląskiej. (in Polish).
[3] Tresa, D. & Amrichová, H. (2006). Automation of casting. *Archives of Foundry.* 6(18), 513-514.
[4] Tresa, D. & Orłowicz, W. (2001). Possibility automatic control of casts. *Acta Metallurgica Slovaca.* 7(3), 437-440.
[5] Craig, I.K., Camisani-Calzdan, F.R. & Pistorius P.C. (2001). A contemplative stance on the automation of continuous casting in steel processing. *Control Engineering Practice.* 9, 1013-1020.
[6] Cuypers, W., Van Gestel, N., Voet, A., Kruth, J.P., Mingneau, J. & Bleys, P. (2009). Optical measurement techniques for mobile and large-scale dimensional metrology. *Optics and Lasers in Engineering.* 47, 292-300. DOI: 10.1016/j.optlaseng.2008.03.013.
[7] Brunke, O. (2012). Fully-automated 3D metrology and defect analysis with high-resolution 300 kV microfocus computed tomography. In 18th World Conference on Nondestructive Testing, 16-20 April 2012 (pp.22-22). Durban, South Africa.
[8] Simon, M. & Sauerwein, C. (2000, October). *Quality control of light metal castings by 3D computed tomography*. Retrieved March 26, 2016, from http://www.ndt.net/article/wcndt00/papers/idn730/idn730.htm
[9] Ratajczyk, E. (2009). Robots and measurement centres. *Pomiary Automatyka i Robotyka*. 3, 6-13. (in Polish).

[10] Kudasik, T., Markowska, O. & Miechowicz, S. (2014). The use of optical coordinate measurements in determining the geometric accuracy of prototypes of cranial implants made by RP technology. *Pomiary Automatyka Kontrola*. 60(4), 195-198. (in Polish).

[11] GOM Company (2015, May). *Precise industrial 3D metrology*. Retrieved March 26, 2016, from http://www.atos-core.com/en/features.php

[12] Luty, G. (2014). Assembly of aircraft structures using photogrammetry systems. *Stal Metale & Nowe Technologie.* 9-10, 158-161. (in Polish).

[13] Vagovský, J., Buranský, I. & Görög, A. (2015). Evaluation of measuring capability of the optical 3D scanner. *Procedia Engineering.* 100, 1198-1206. DOI: 10.1016/j.proeng.2015.01.484.

[14] Tomasiak, J. (2014). The use of optical methods for leak testing dampers. *Procedia Engineering.* 69, 788-794. DOI: 10.1016/j.proeng.2014.03.055.

[15] Jaworski, J., Kluz, R. & Trzepieciński, T. (2013). Capability assessment of robotized system for casting measurement. *Archives of Foundry Engineering.* 13(1), 57-60.

[16] Kluz, R. & Trzepieciński, T. (2015). Analysis of the optimal orientation of robot gripper for an improved capability assembly process. *Robotics and Autonomous Systems.* 74, 253-266. DOI: 10.1016/j.robot.2015.08.007.

[17] Adamczak, S. & Makieła W. (2010). *Fundamentals of Metrology and Quality Engineering for Mechanics. Practical Exercises.* Warszawa: Wydawnictwa Naukowo-Techniczne. (in Polish).

[18] Slezák, P. & Waczuliková, I. (2011). Reproducibility and repeatability. *Physiology Research.* 60, 203-205.

[19] Diering, M. & Pająk, E. (2010). Running evaluation the usefulness of measuring systems during manufacturing process - Part I: methodology. *Zarządzanie Przedsiębiorstwem.* 1, 2-13. (in Polish).

[20] Sikora, M. (2005). General tolerances of castings *Archives of Foundry.* 5(17), 263-272. (in Polish).