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DETERMINATION OF MINIMAL MACHINING ALLOWANCES IN IRON CASTINGS

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Summary

Method of assessing of minimal machining allowances of casts using optical measurement is introduced. Inclination of technological surfaces, their flatness error as well as positioning of the workpiece on the machine tool have been taking into account. The minimal values of allowances are calculated based on the acquired cloud of points representing the surface, which is subsequently substituted with plane according to 3D least square method. Flatness error is calculated and used for determining the value of allowance on single surface by vector analysis. Minimization of volume to be machined by implementing genetic algorithm is presented. Minimal allowances obtained by the method constitute the constraints for further minimization of removed volume. Three sets of casts were measured and minimal machining allowances were determined and compared with ISO 8062:1997 and DIN 1680-1:1980 standards. Optimization of machining allowances results in decreasing the time and costs of manufacturing.

Keywords: marking-out, machining, photogrammetry, 3D scanning, genetic algorithms, optimization

Wyznaczanie minimalnych naddatków obróbkowych w odlewach żeliwnych

Streszczenie

W artykule określono minimalne naddatki obróbkowe metodą optyczną. Uwzględniono pochylenia technologiczne obrabianych powierzchni, błędy kształtu oraz dokładność pozycjonowania obrabianego odlewu na obrabiarce. Minimalne wartości naddatków ustalono na podstawie analizy chmury wartości współrzędnych punktów pomiarowych reprezentującej powierzchnię obrabianego odlewu. Wprowa-dzono płaszczyzny średnie wyznaczone metodą najmniejszych kwadratów. Algorytm genetyczny przyjęto jako metodę minimalizacji objętości materiału usuwanego w trakcie obróbki. Najmniejsze wartości naddatków stanowią granice minimalizacji objętości wiórów. Weryfikację przyjętych założeń prowadzono dla trzech różnych zestawów odlewów. Porównano wartości minimalne naddatków z wartościami normatywnymi wg ISO 8062:1997 oraz DIN 1680-1:1980. Minimalizacja objętości materiału skrawanego wpływa na zmniejszenie kosztów wytworzenia wyrobu i zmniejszenie czasu pracy obrabiarki.

Słowa kluczowe: trasowanie, obróbka skrawaniem, fotogrametria, skanowanie 3D, algorytmy genetyczne, optymalizacja

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Introduction

In manufacturing process that copes with large and complicated parts obtained by casting the first stage is to prepare a workpiece by leveling it and marking the machining datum surfaces. As researched by Matusiak-Szaraniec [1] a typical machine body encompasses average 15-20 technological facets. There are machining allowances left on them which values ensure further successful machining. They are standardized by international standards (ISO 8062:1997, DIN 1680-1:1980) [2, 3], but their size results mostly from the casting process. Jiang and Liu researched the accuracy of casting process in the ceramic moulds [4], while Shareef investigated casting processes based on green-sand and encapsulated-sand [5].

Without considering casting defects such as inclusions and porosity, the minimal value of machining allowance is the distance between maximal and minimal point of the raw surface, measured in the direction of Z axis of the machine tool. Due to technological reasons, the surfaces of the cast which, theoretically parallel or inter-perpendicular, are inclined relative to each other and their flatness and roughness is relatively poor. Initial fixing the workpiece on the machine tool is based on raw surfaces resulting in additional rotation of machined facets in respect to the coordinate system of the machine tool. All these phenomena cause that minimal values of the allowances depend directly on the geometrical quality of cast as well as its orientation in respect to the machine tool coordinate system. Actual machining allowances result from cast orientating and fixing on machine tool in reference to the marking scratches. There are procedures for optimizing the allowances, e.g. Shen et al. developed an algorithm for calculating the optimal location of casting [6]. Application of HSM technology requires minimization of the machining volume, which was researched by Fallböhmer at al. [7].

The problem of determining the minimal allowances in castings stems from the idea of optimal positioning of the cast with respect to its machined surfaces. The cast geometry, obtained e.g. by means of coordinate measurement techniques, is aligned with reference model by translating and/or rotating either the scan or the model. The amount of the material to be removed depends on the six independent displacements: three translational and three rotational which determine the average distance between respective raw and theoretical surfaces. Figure 1 depicts the idea of layout process for one surface to be machined. Level, represented by two rotations, is adjusted and two parallel lines indicating the particular theoretical dimension are marked by scriber leaving some material for removal.

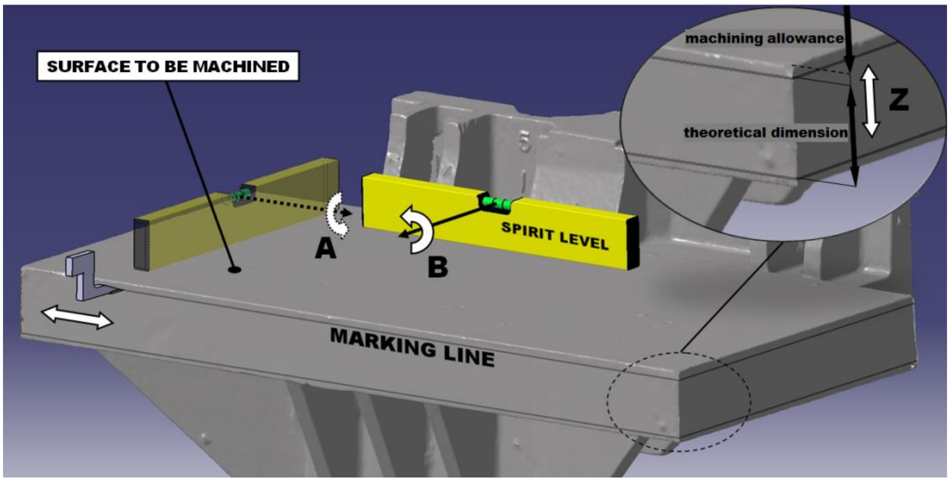


Fig. 1. Layout process

ISO and DIN standards [2, 3, 8] provide the minimal values of machining allowances, for cast of certain size and obtained by the specific technology, which would ensure the successful machining. However, multitude of manufacturers issue and follow their own internal standards which more strictly comply with their needs.

Foundation and methodology

Optical measurements techniques provide the data concerning the location of individual points of the measured piece (Fig. 2). The cloud of points can be used for estimation of surface roughness [9] or geometric deviations of the measured casting [10]. The measured surface can be described in the local coordinate system by the function

$$z_p = f(x, y) \tag{1}$$

Since only limited number of points is acquired from the measurement and its flatness is relatively high, the real surface is substituted with a plane:

$$z_i = ax_i + by_i + c \tag{2}$$

where coefficient are calculated by 3D least square method by solving the following set of the equations:

$$\begin{bmatrix} \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} y_i^2 & \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} y_i & n \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} x_i z_i \\ \sum_{i=1}^{n} y_i z_i \\ \sum_{i=1}^{n} z_i \end{bmatrix} \tag{3}$$

where n is the number of points which constitute the surface.

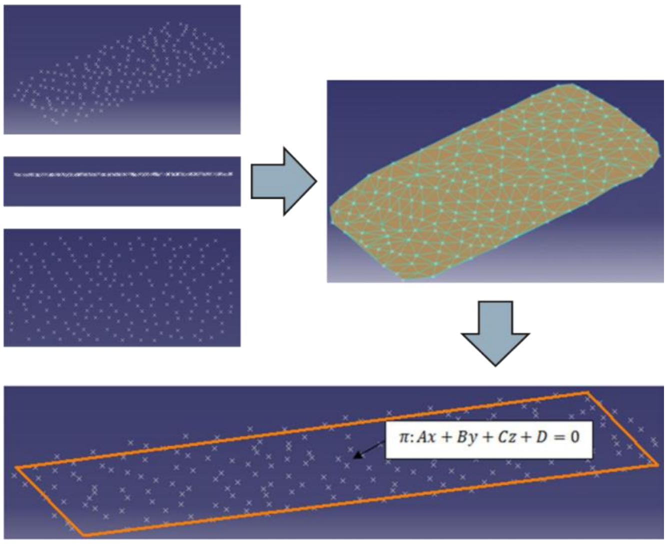


Fig. 2. Measured cloud of points substituted with nominal plane

The substituted plane characterizes the average value of angle at which it is oriented relative to its local coordinate system. Basing on the relation (3), the angles between the plane and the axis of local coordinate systems can be calculated by the formula:

$$\alpha = \arccos\left(\frac{a}{\sqrt{a^2 + b^2 + 1}} \right) \tag{4}$$

$$\beta = \arccos\left(\frac{b}{\sqrt{a^2 + b^2 + 1}} \right) \tag{5}$$

$$\gamma = \arccos\left(\frac{-1}{\sqrt{a^2+b^2+1}}\right) \tag{6}$$

where: α – angle between the plane and X axis of the local coordinate system, β – angle between the plane and Y axis of the local coordinate system, γ – angle between the plane and Z axis of the local coordinate system.

The distance between the maximum and the minimum point of the surface is calculated based on ISO definition of flatness (ISO 1101:2006) where the two parallel planes within which the surface must be located are parallel to the substituted plane (3). If δ is the distance between the point of surface and the mean plane than flatness error is given by the formula:

$$d = \delta_{max} - \delta_{min} = \frac{|ax_{max} + by_{max} - z_{max} + c|}{\sqrt{a^2+b^2+1}} - \frac{|ax_{min} + by_{min} - z_{min} + c|}{\sqrt{a^2+b^2+1}} \tag{7}$$

where: x_{max}, y_{max}, z_{max} – coordinates for the most distant point lying above the plane, x_{min}, y_{min}, z_{min} – values of coordinates for the most distant point lying below the plane.

The minimal allowance is calculated taking into consideration the rotation of workpiece in the local coordinate system in relation to machine tool system by the set of angles. The allowance can be calculated as the distance between the maximal and minimal point, projected onto axis which is normal to reference plane (after the machining) of the reference model. Knowing the the coordinates of the extreme points and angular orientation of the substituting plane, minimal values of the allowances h_{ix}, h_{jy}, h_{kz} for corresponding i, j, k – reference surfaces oriented in X, Y, Z direction of the reference coordinate system, correspondingly.

$$h_{ix} = \left| T_{rot}^{Y} \cdot T_{rot}^{Z} \cdot [\Delta x \quad \Delta y \quad \Delta z] \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right| \tag{8}$$

$$h_{jy} = \left| T_{rot}^{X} \cdot T_{rot}^{Z} \cdot [\Delta x \quad \Delta y \quad \Delta z] \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \right| \tag{9}$$

$$h_{kz} = \left| T_{rot}^{X} \cdot T_{rot}^{Y} \cdot [\Delta x \quad \Delta y \quad \Delta z] \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right| \tag{10}$$

where: $\Delta x = x_{\max} - x_{\min}$, $\Delta y = y_{\max} - y_{\min}$, $\Delta z = z_{\max} - z_{\min}$ – difference of the coordinates of maxima and minimal point of the surface described in the local coordinate system, T^X_{rot}, T^Y_{rot}, T^Z_{rot} – transformation matrices of coordinate system – rotation around *X*, *Y*, *Z* axis of reference coordinate system:

$$T^X_{\text{rot}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha + \Delta\alpha) & -\sin(\alpha + \Delta\alpha) \\ 0 & \sin(\alpha + \Delta\alpha) & \cos(\alpha + \Delta\alpha) \end{bmatrix} \tag{11}$$

$$T^Y_{\text{rot}} = \begin{bmatrix} \cos(\beta + \Delta\beta) & 0 & \sin(\beta + \Delta\beta) \\ 0 & 1 & 0 \\ -\sin(\beta + \Delta\beta) & 0 & \cos(\beta + \Delta\beta) \end{bmatrix} \tag{12}$$

$$T^Y_{\text{rot}} = \begin{bmatrix} \cos(\gamma + \Delta\gamma) & -\sin(\gamma + \Delta\gamma) & 0 \\ \sin(\gamma + \Delta\gamma) & \cos(\gamma + \Delta\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

where: α, β, γ – angles derived from equations (4), (5) and (6), $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$ – angular errors of positioning the cast on the machine tool table.

Idea of determining the minimal allowance is depicted in Fig. 3.

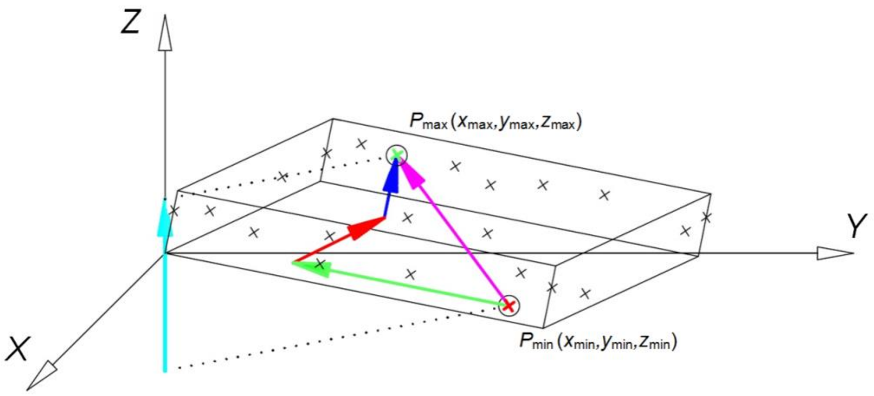


Fig. 3. Minimal machining allowance as sum of three vectors projected onto normal *Z*-axis

Value of minimal allowance depends not only on the geometry of surface to be machined but also on orientating the cast on machine tool. By multiplying the areas of all surfaces by their respective minimal allowances, the minimal volume to be machined as the function of $(\Delta\alpha, \Delta\beta, \Delta\gamma)$ can be calculated by the following formula:

$$V(\Delta\alpha, \Delta\beta, \Delta\gamma) = \sum_{i=1}^{m} A_i r_{ix} + \sum_{j=1}^{n} A_j r_{jy} + \sum_{k=1}^{o} A_k r_{kz} \qquad (14)$$

gdzie: *m, n, o* – the numbers of planes normal to *X*, *Y*, *Z* axis of local coordinate system respectively, A_i, A_j, A_k – areas of surface to be machined normal to *X*, *Y*, *Z* axis of local coordinate system respectively.

A mean machining allowance r_{ix}, r_{jy}, r_{kz} can be defined as the length of vector, which begins from the point located extremely below the substituting plane and ends at any point lying on the substituting plane, projected on the normal direction of reference plane (after machining).

The predicted volume of machined material takes a minimal value for certain values of rotation angles between the local and machine tool coordinate system $(\Delta\alpha, \Delta\beta, \Delta\gamma)$. Due to occurrence of trigonometric functions, analytical method of calculating the extreme value of function of three variables by solving the following set equation:

$$\begin{cases} \dfrac{\partial V}{\partial \Delta\alpha} = 0 \\ \dfrac{\partial V}{\partial \Delta\beta} = 0 \\ \dfrac{\partial V}{\partial \Delta\gamma} = 0 \end{cases} \qquad (15)$$

with respect to the set of angles is troublesome. Therefore computational method of differential evolution [11] is introduced to solve the problem, which is described as efficient and precise algorithm. The values for which the volume takes minimum are then used for calculating the minimal allowances. The minimal allowances together with rotational position of the piece in relation to the machine tool constitute the set of constraints for further minimization of machining volume, which is a subject of patent application [12].

Measurement and results

Initial measurement of sets of different size and shape casts were conducted in order to determine the minimal of machining allowances. In the first stage, reference markers were sticked onto casts surfaces for the further scanning process by ATOS II by GOM (Fig. 4).

Fig. 4. Measured cast with reference elements of optical system

The size of scanned area and the number of capturing sequences were determined by the camera system as well as its maximum scanning area. During the scanning it was necessary to rotate the piece in order to capture its entire body. As a result of using ATOS II by GOM, complete geometrical models were derived. M. Wieczorowski at al. proposed using scanned models for checking quality of molds and cores [13] and verification of casting shape [14], while Cuypers et al. pointed out the possibility of optimization of machining allowances [15].

The initial coordinate system was introduced which refers to fixing point on the machine tool. The software allows to create the mean plane, which parameters characterize the substituted surface (Fig. 5).

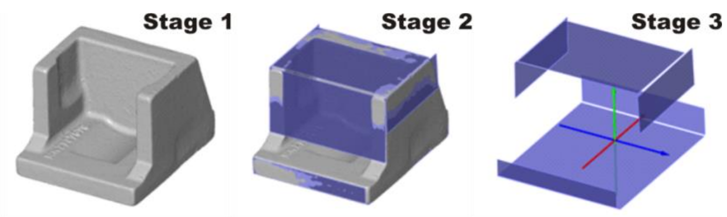


Fig. 5. The process of measurement: stage 1 – capturing coordinates of the cloud of points constituting the cast, stage 2 – substituting the selected surfaces by planes, stage 3 – introducing initial local coordinate system

The angles between the surfaces and respective axis as well as the flatness according to ISO standard was obtained (Fig. 6). Surface flatness is represented as the distance between two parallel planes, parallel to the substituting plane, within which the surface is located.

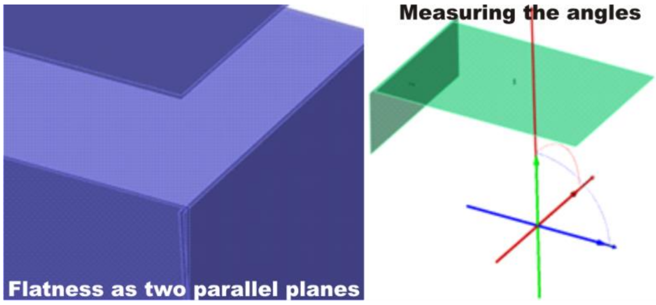


Fig. 6. Introducing the plane characterizing the machining surfaces and measuring the angles between the plane and respective axis and the flatness

The subject of the research were three sets of casts of various geometry which are parts of machine tool body. The measured values of flatness as well as the angles between the substituting planes and the introduced local coordinate systems were used for the calculation of the minimal allowances, taking into account the minimization of volume of the material to be removed. It was assumed that the cast was orientated so as to ensure the first machined surfaces to be normal to the spindle.

Minimization of volume was conducted by Wolphram Mathematica Software built-in optimization function based on differential evolution algorithm. The set of angles $(\Delta\alpha_{\min}, \Delta\beta_{\min}, \Delta\gamma_{\min})$ were derived for every minimized cast. The figures were subsequently used for calculating the minimal value of allowances according to the presented methodology. The example function of volume $V = f(\Delta\alpha, \Delta\beta)$ for the minimal value of $\Delta\gamma$ is depicted in Fig. 7.

The values of minimal allowances for the measured casts are presented in Fig. 8 and 9.

ISO 8062:1997 and DIN 1680-1:1980 standards suggest size of machining allowances in relation to the material, technology and size of the casted part. However, before comparing obtained values of machining allowances with the normal ones, inclinations of surfaces to be machined have to be taken into consideration.

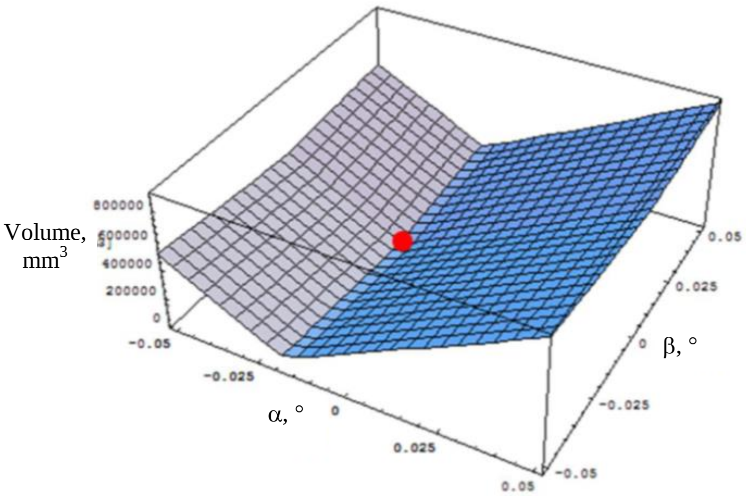


Fig. 7. The predicted volume of removed material of cast 2.1 for the minimized value of rotational displacement around Z axis of machine tool

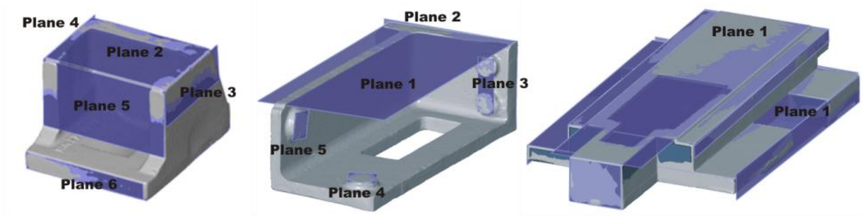


Fig. 8. Analyzed planes of measured casts

a)

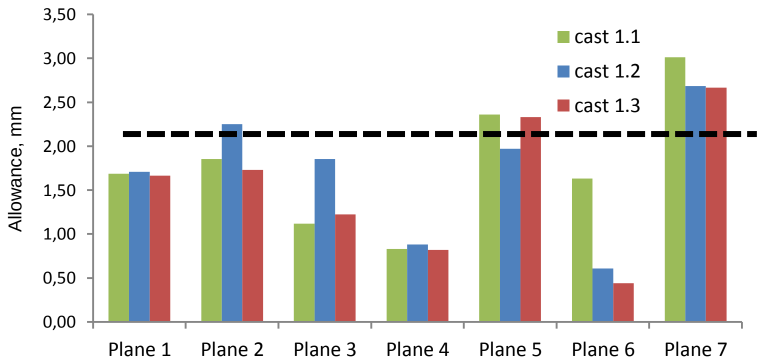
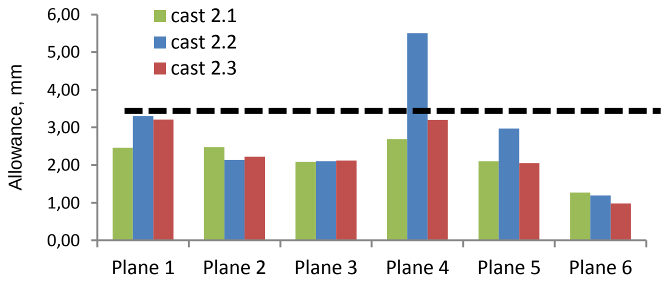


Fig. 9. The minimized allowances distribution for the series of research pieces (dashed line – minimal allowance according to ISO 8062:1997) for casts: a) 1.1,

b)



c)

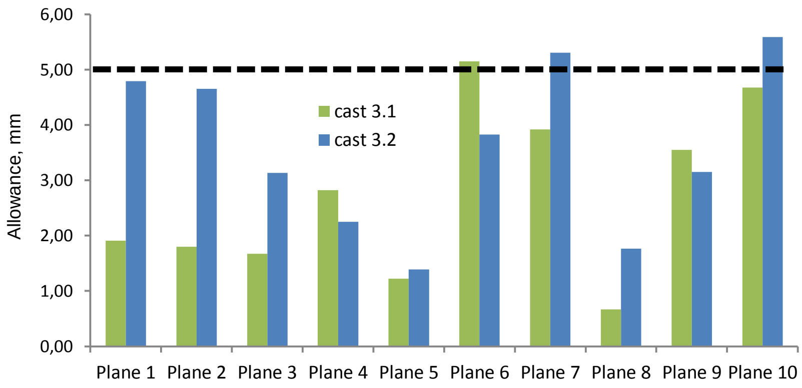


Fig. 9. The minimized allowances distribution for the series of research pieces (dashed line – minimal allowance according to ISO 8062:1997) for casts: b) 2.1, 2.2, 2.3, c) 3.1, 3.2

Conclusions

The method of assessing minimal value of machining allowances for casts, taking into account their geometry as well as their fixing on machine tool has been devised. The obtained results can be used as constraints for further minimization of total volume of material to be removed by comparing the acquired, by means of optical measurements, model with its CAD reference model.

Maximal allowances obtained by the presented method are similar to the values defined by ISO and DIN standards. However, for majority of measured casts, the values are below normal what creates the opportunity to reduce total volume of machined material resulting in significant decrease of the time of machining and wearing of machinery and tools. In addition, by stabilizing the casting process, it is possible to identify the surfaces where the allowances can be reduced by the producer leading to substantial decrease of casting mass and, therefore to reduce the costs of manufacturing and further processing.

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