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Optimizing Body Machining Including Variable Casting Allowances

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Abstract
The work contains the results of research conducted to optimize the machining of milling table castings. The possibility of reducing the total volume of machining allowances, reducing the wear of cutting tools, shortening machining time and eliminating idle machining passes was considered. The tests were carried out on two batches of castings supplied by two independent foundries. Casting geometry measurements were made using a structured light scanner. The analysis included machining with cemented carbide tools and tool ceramics at two machining centers: DMC200U and DMC270U. It has been shown that as a result of eliminating idle machining passes, it is possible to reduce machining time by 12% for the first and by 44% for the second casting supplier. The estimated annual savings for the production volume of 500 pcs of these castings can range from € 7388 to even € 23 346. The actual cost of cheaper casts was also calculated, taking into account the difference in machining cost resulting from larger machining allowances.

Keywords
cast iron geometry assessment, machining allowances, machining cost minimization.

Introduction

Casting is an economical way of producing cast iron machine tool bodies. The amounts of allowances assumed on machined surfaces result from the grade of cast iron, casting methods and casting dimensions. In determining them, they are guided by the relevant standards: national, international or also their own (DIN ISO 8062-3). The amount of machining allowance directly affects the quality of the machined surface and machining efficiency, and thus also affects the cost of production (Li et al., 2013). The issue of improving quality and reducing production costs in the mechanical industry is widely discussed in scientific publications and doctorates (Nicolaou at al., 2002; Schreiner, 1999). Some casting defects can be excluded due to advanced simulations of the casting process (Sika et al., 2019).

The amount of machining allowances affects the technological load by cutting forces. For this reason, a correctly designed and manufactured fixture is of great importance during machining (Bazrov and Sorokin, 1982). Research is also carried out on the impact of the use of a cooling lubricant on the cost and quality of machining (Berry, 2000).

In order to minimize the cost of finished products, as well as provide them with the highest quality, many researchers are involved in minimizing machining allowances. The authors (Li et al., 2013) proposed an innovative two-stage approach to the automatic estimation of machining allowance during precision casting, based on the analysis of planes obtained from the measured point cloud. Evaluation of machining can be carried out in a few seconds with the same accuracy as the accuracy of the measured point cloud. This method can improve process efficiency and allow for automatic assessment of machining allowance. Another research team (Sun et al., 2009; Zhang et al., 2015) developed a different approach to optimizing machining allowances. These researchers proposed a way to optimize allowances for complex parts based on CMM inspection (Zhang et al., 2015). This technique uses a centering process to ensure sufficient material surplus for individual parts as well as entire integrated parts. A mathematical model was first established and then a symmetric block solution strategy was proposed to solve the optimization model.

In contrast, researchers (Sun et al., 2009) have developed a unified location technique for machined surfaces to meet a user-defined set of constraints for specific surfaces, where machining allowance must be guaranteed in a certain amount.

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Optimization of the position and orientation of the blank in the machining space is the subject of many studies aimed at, on the one hand, ensuring a positive allowance on each machined surface (Chatelain, 2005), on the other hand, the aim is to position the blank so that the sum of allowances machined is as low as possible (Chatelain and Fortin, 2001). Optical measuring systems for measuring the blank before machining (Cuypers et al., 2009) are successfully used in the optimization process, as well as attempts to build such systems in the machining space (Mendikute and Zatarain, 2012). The actual cast model scanned before machining is often used in the process of tool path optimization (Dai et al., 2010; Koikea et al., 2013).

Some researchers (Wu and Dai, 2016) believe that it is necessary to control each process to make sure that the final quality of the final product is stable. In multistage production processes, there are many variable factors that inevitably lead to numerous manufacturing defects that could compromise the quality of the final product. In order to reduce these drawbacks, the mentioned team of scientists in the article proposed a model for measuring the quality of products, which was associated with multi-degree tolerance of machining allowances. Then they used it to optimize allowances in a multi-stage production process. The model of the real blank is necessary not only for the needs of quality control, but also for the development of the machining program in modern CAM systems (Kowalski and Zawadzki, 2019), as well as for the needs of advanced numerical analyzes (Hamrol et al., 2019).

Cost optimization of machining processes requires knowledge and processing of a number of detailed information, including batch size, machining times, tool and machine costs (Sanghavi et al., 2019). This becomes particularly important in the context of implementing solutions from the Industry 4.0 area (Pekarcikova et al., 2019).

In the process of production optimization as such, correctly performed simulations of material flow are of great importance, which allows for a significant increase in production efficiency (Rewers et al., 2019).

The author's earlier research works were related to the development of a method for assessing the accuracy of castings using an optical measuring system (Gessner et al., 2014a), determining the minimum allowances due to shape errors of the cast surfaces (Gessner et al., 2014b), optimizing the distribution of allowances, including according to criterion of the hardness of the processed surface (Gessner and Staniek, 2014; Gessner, 2016), as well as the possibility of their automatic setting for processing (Gessner and Adam, 2016).

Purpose and scope of work

The aim of the research work was:

- assessment of the amount of allowances in the same castings made by different foundries,
- reducing the number of machining passes,
- elimination of sterile machining transitions (machining in the air).

Expected benefits:

- shorter machining time,
- longer tool life,
- lower cost of producing the body.

Subject and research methodology

Two production batches of body castings of medium size milling tables were tested. The batches were made by two different foundries: operating on the European market (18 pieces) and the Asian (32 pieces). The diagram scheme of the procedure for carrying out research is presented in Fig. 1.

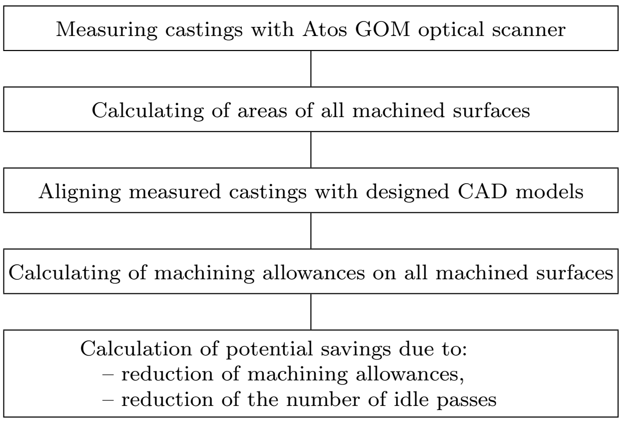


Fig. 1. Diagram scheme of the procedure for carrying out research

A pictorial view of the tested casting fixed in the machining device is shown in Fig. 2. Its weight after machining is 426 kg.

Castings were measured using the Atos GOM automated measuring system, working on the basis of analysis of the distribution of measuring fringes. Measurements were carried out in a separate measuring cell, castings for tests were placed in the same position using a modular measuring instrument (Fig. 3). Magnetic beams with reference markers were mounted on selected casting surfaces, which were automatically removed during the processing of measurement data.

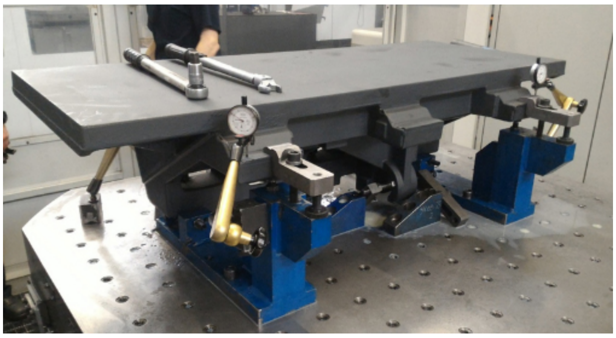


Fig. 2. Subject of analysis – milling center table casting

The same number and orientation of measuring intakes were used for each measured casting. The view of the casting during measurements is shown in Fig. 3.

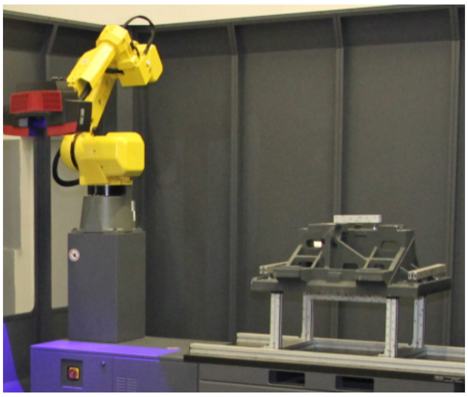


Fig. 3. Table in the measuring cell

In the tested castings, machined surfaces were first grouped according to their direction, and then according to their function (Fig. 4):

- surfaces perpendicular to the Z axis direction:
  - top surface,
  - pockets,
  - truck surfaces,
- surfaces perpendicular to the X axis:
  - right side walls,
  - left side walls,
  - back nut surface,
  - front nut surface,
- surfaces perpendicular to the Y axis:
  - front surface,
  - back surface,
  - front support surfaces,
  - back support surfaces,
  - side nut surface.

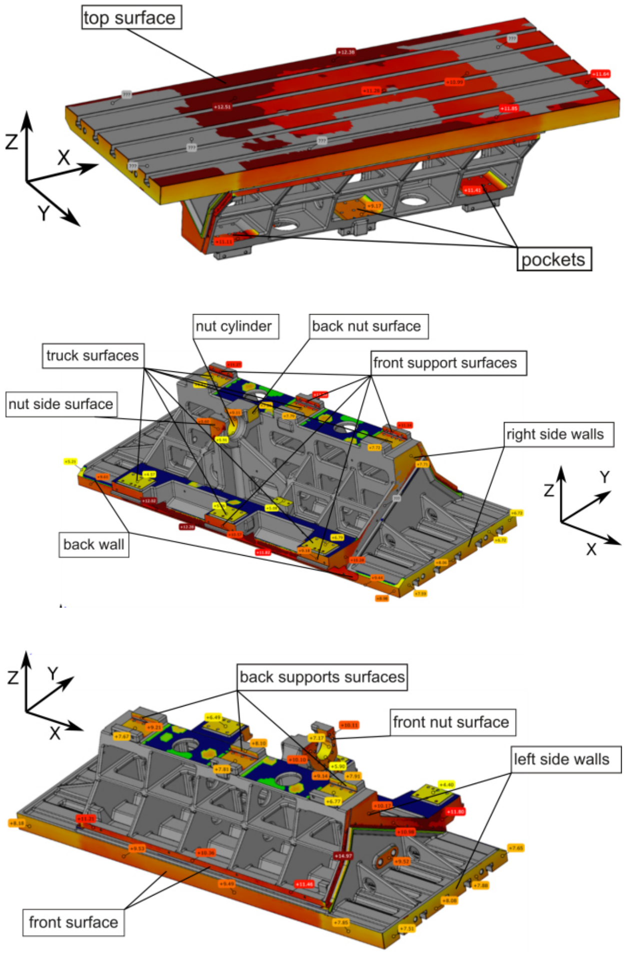


Fig. 4. Groups of tested surfaces in the analyzed table casting

The cylindrical inner surface of the cap was separated. Inclined side surfaces with a low percentage as a whole were not taken into account.

Table 1 summarizes the surface areas and the percentage share in total of all analyzed machined surfaces. The surfaces were grouped according to the directions of the coordinate system axes. Figure 5 graphically presents the percentage share of machined surfaces depending on the casting side.

The values of allowances on machined surfaces were obtained from the comparison of the measured cast model with the structural model (model of the designed body after machining). Mutual matching of both models was performed using the *best-fit* function (the best fit of both models based on all surfaces) of the scanning system software. The allowance value for each surface was calculated as the median distance of the measured points from the worked surface.

The first machining operation of the tested castings, according to the production plan, is performed

Table 1
Estimated surface areas of individual groups of machined surfaces

Surface (side)	Area [mm^2]	Participation (X, Y, Z) [%]	Participation in full [%]
	Z direction		
top surface (+)	784 000	90.1	64.5
pockets (+)	42 051	4.8	3.5
truck surfaces (–)	43 800	5.0	3.6
total for *Z*	**869 851**	**100.0**	**71.5**
	X direction		
right side walls (+)	63 682	43.4	5.2
back nut surface (+)	2 279	1.6	0.2
left side walls (–)	70 147	47.9	5.8
nut surface (–)	10 472	7.1	0.9
total for *X*	**146 580**	**100.0**	**12.1**
	Y direction		
front support surface (–)	18 624	10.0	1.5
nut side surface (–)	4 268	2.3	0.4
back wall (–)	64 016	34.2	5.3
back support surface (+)	6 016	3.2	0.5
front surface (+)	94 144	50.3	7.7
total for Y	**187 068**	**100.0**	**15.4**
nut cylinder	12 401		1.0
Total	**1 209 191**		**100.0**

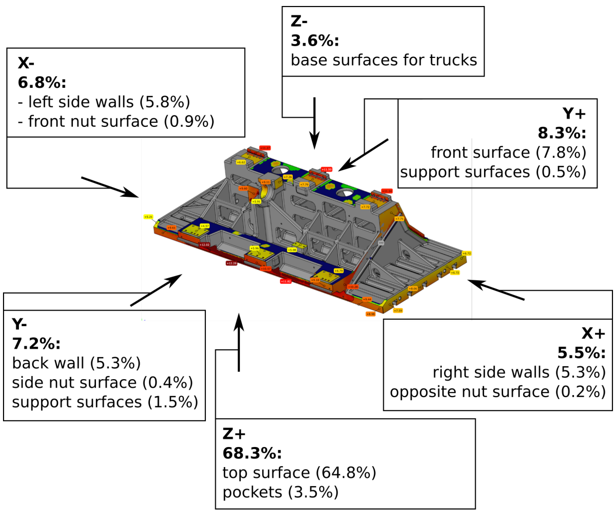


Fig. 5. Percentage of processed surfaces depending on the casting

on one of the two machining centers DMC200U or DMC270U. When considering machining costs, different hourly rates for both of these machines were therefore taken into account: € 61.6 for DMC200U and € 82.23 for DMC270U, respectively. During the research, tests related to the implementation of tool ceramics for processing were also conducted. For this reason, the processing times for each of these technologies were also different. The material cost of 1 kg of casting was adopted as € 1.1. This is an average value, calculated on the basis of casting prices from both suppliers, taking into account the volume of orders.

Analysis of results – machining allowances

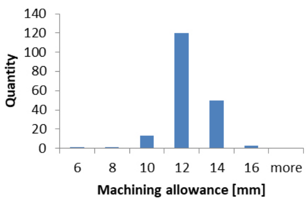
In the first step, a comparison of selected castings from both foundries was made (Fig. 6). The comparison was made by matching both models using the *best-fit* function. The results were presented in the form of a color map of deviations applied to the casting model made by the European foundry. It was found that the raw casting surfaces are compatible, while the differences occur on the treated surfaces. In castings supplied by the Far Eastern supplier, these allowances were usually higher. A detailed comparison of allowances showed that the differences in countertop surfaces were up to two times.

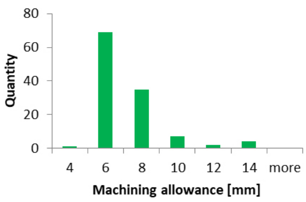
For groups of surfaces in accordance with the direction of the Z axis, histograms of their allowances were made, the maximum and minimum allowance was determined, and the median and standard deviation were calculated. The width of the histogram class interval was assumed to be 2 mm – analogically to the machined layer in one machining pass. The results are presented in Table 2.

Table 2
Histograms of allowances for individual machined surfaces in the Z axis direction

Asian foundry | European foundry

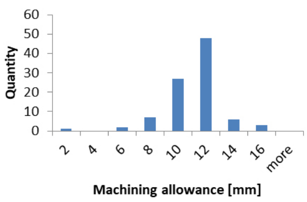
TOP SURFACE

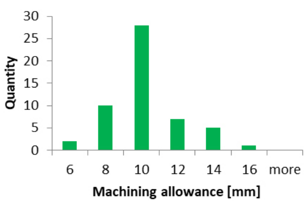




Asian foundry	European foundry
max allowance: 14.77 mm	max allowance: 12.79 mm
min allowance: 8.23 mm	min allowance: 3.68 mm
median: 11.34 mm	median: 5.61 mm
std dev: 1.08	std dev: 1.77

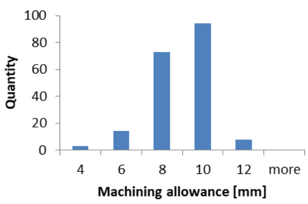
POCKETS

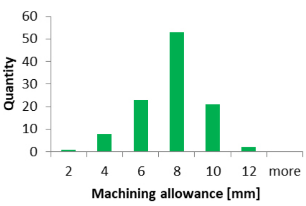




Asian foundry	European foundry
max allowance: 15.89 mm	max allowance: 14.07 mm
min allowance: 2.00 mm	min allowance: 5.46 mm
median: 10.59 mm	median: 9.00 mm
std dev: 1.98	std dev: 1.97

TRUCK SURFACES





Asian foundry	European foundry
max allowance: 11.77 mm	max allowance: 10.35 mm
min allowance: 2.96 mm	min allowance: 1.57 mm
median: 8.11 mm	median: 6.87 mm
std dev: 1.35	std dev: 1.80

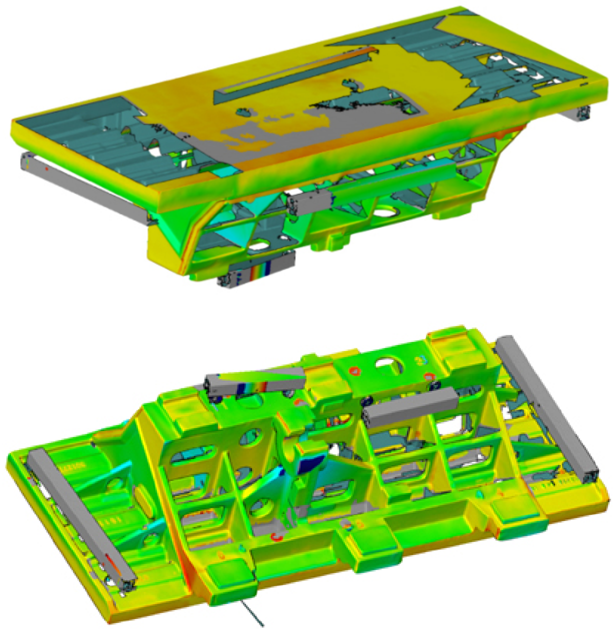


Fig. 6. Comparison of castings from both suppliers

Possibilities for reducing allowances

Table 3 shows the potential reduction in the material cost of castings from a Far Eastern supplier due to matching their machining allowances with the values used by the other supplier. A simplifying assumption was made that the volume of machining allowance for a given group of surfaces is calculated as the product of this area and the median of the value of the allowance of the analyzed group. The cost of 1 kg of casting was adopted at the level of € 1.1. The potential reduction in the cost of a Far East supplier is € 45.54, which is 8% of the cost of casting in this foundry.

Changes in the shape of castings require costly modifications to the casting molds. Due to the fact that the worst part has the largest percentage in the total machined surfaces, and its surface is characterized by good repeatability, further cost reduction analysis was carried out based on reducing only this allowance. The variants considered took into account the current and planned technology to be implemented: machining with a 125 mm diameter head with cemented carbide plates (current technology), and a 80 mm diameter head with ceramic plates (planned technology). Technological parameters for both cases are presented in Table 4.

As a result of the comparison, it was found that reducing the allowance only on the table surface by 2 mm (one machining pass) reduces the weight of the

Table 3
Potential reduction of the cost of castings supplied by the Asian foundry

Type of surface	Area [mm^2]	Allowance median [mm]		A–E [mm]	weight reduction [kg]
		Asian	European		
top surface	784 000	11.3	5.61	5.69	31.58
pockets	42 051	10.59	9	1.59	0.47
truck surfaces	43 800	8.11	6.87	1.24	0.38
side walls	133 829	8.85	4.5	4.35	4.12
nut surface	10 472	8.74	9.03	–0.29	–0.02
front support surface	24 640	10.12	6.4	3.72	0.65
back wall	64 016	9.88	3.97	5.91	2.68
front surface	94 144	8.86	7.24	1.62	1.08
nut cylinder	12 401	8.79	4.09	4.7	0.41
casting weight reduction [kg]					**41.40**
reduction of casting cost [EUR]					**45.54**

Table 4
Cutting parameters used for machining top surface

Parameter	Carbide sintered	Ceramics
head diameter D [mm]	125	80
number of inserts n_i	8	5
number of cutting edges per insert n_{ce}	16	8
cutting speed v_c [m/min]	235	1400
feed v_f [mm/min]	1050	14 000
cutting thickness a_p [mm]	2	2
cutting edge life T [min]	60	30
cutting insert life T_i [min]	960	240
insert cost K_i[EUR]	11	17
cutting path s [mm]	10 133	25 437
cutting time for one layer of the worktop surface t_{bl} [min]	10	1.87

casting by 11.1 kg, and as a result its cost by € 12.21. Annual savings for 500 castings will be € 6105. Instead, reducing the allowance only on the table surface by 4 mm (two machining passes) reduces the weight of the casting by 22.2 kg, and as a result its cost by € 24.42. In this case, the annual savings for 500 castings will be € 12 210.

Possibilities to reduce machining time and wear of cutting tools

The analysis of cutting tool wear reduction was carried out for the worktop surface with carbide inserts and ceramics. The tools and parameters used are shown in Table 5.

Table 5
Savings calculated for 500 pieces of castings

Savings calculated for 500 pieces of castings	Carbide sintered	Ceramics
shortening the time for one pass for 500 castings [min]	5 000.00	935.00
shortening the time for two passes for 500 castings [min]	10 000.00	1 870.00
tool cost for one pass [EUR]	434.44	323.11
tool cost for two passes [EUR]	868.88	646.23
machine cost for one pass (DMC270U) [EUR]	6 852.29	1 281.38
machine cost for two passes (DMC270U) [EUR]	13 704.58	2 562.76
machine cost for one pass (DMC200U) [EUR]	5 134.28	960.11
machine cost for two passes (DMC200U) [EUR]	10 268.56	1 920.22

The shortening of the transition time was calculated as the product of the feed speed v_f and the cutting path s.

$$t_{\text{red}} = v_f \cdot s \ \ \text{[min]}. \tag{1}$$

The annual cost of insert (for 500 castings) for one machining pass was calculated according to the equation:

$$K_1 = (t_{bl} \cdot 500 \cdot n_i \cdot K_i)/(T \cdot n_{ce}) \,. \tag{2}$$

The annual savings in the cost of the machine (for 500 castings) were calculated as the product of the reduction of the time of one pass and the hourly rate of the machine, respectively € 61.6 for DMC200U and € 82.23 for DMC270U:

$$K_2 = t_{\text{red}} \cdot K_{\text{machine\_tool}} \ \ [€]. \tag{3}$$

Table 5 shows the results obtained calculated for the annual production of 500 pieces of given castings.

For carbide machining, reduce allowance by 2 mm only on the top surface per year 500 pieces of castings will reduce the working time by 5000 minutes, which will reduce the cost of inserts by € 434,44. Depending on the machine tool used, this will also reduce its cost by € 5134 (DMC200U) or € 6852 (DMC270U).

For ceramics, reducing the allowance by 2 mm only on the top surface per year for 500 pieces of castings will shorten the working time by 935 minutes, which will reduce the cost of inserts by € 323. Depending on the machine tool used, this will also reduce its cost by € 960 (DMC200U) or € 1281 (DMC270U).

Possibilities to reduce the number of idle machining passes (reduction of machine time)

Due to the fact that the technology department develops one machining program for a given casting (regardless of the supplier), the number of cutting passes for a given group of surfaces results from the tools used (different a_p values) and the maximum machining allowance. Each machining program is verified in simulation software in terms of determining the machining time, as well as eliminating the potential risk of collision. The consequence of this approach are sterile machining passes in castings, in which smaller allowances on machined surfaces were made. This problem is especially evident when a given cast is supplied by contractors using various allowances.

Earlier analyzes of the potential reduction of machining costs concerned improvements on the foundry side-reduction of machining allowances. By using the scanner in the process of preparing castings for machining, it is possible to reduce the machining cost by reducing the number of machining passes. For each measured casting it is possible to obtain information regarding actual machining allowances on all surfaces.

Table 6
The number of machining passes for the table top surface of the Asian foundry and their possible reduction

No of casting	$a_{p\_\max}$ [mm]	$a_{p\_\min}$ [mm]	No of passes
A-1-1	12.51	10.99	7
A-1-2	14.08	10.94	7
A-1-3	9.45	8.23	5
A-1-4	12.75	10.97	7
A-1-5	12.83	11.02	7
A-1-6	12.42	11.01	7
A-2-1	11.54	10.27	6
A-2-2	12.52	10.57	7
A-2-3	12.35	10.96	7
A-2-4	12.57	11.31	7
A-2-5	12.09	10.01	6
A-2-6	13.05	10.35	7
A-2-7	10.6	8.51	7
A-3-1	12.08	10.83	6
A-3-2	12.78	10.53	7
A-4-1	12.59	11.29	7
A-4-2	12.2	10.5	7
A-4-3	13.21	10.7	7
A-5-1	12.82	11.03	7
A-6-1	12.18	10.21	7
A-6-2	12.31	5.93	7
A-6-3	11.92	10.17	6
A-6-4	12.5	10.84	7
A-6-5	12.63	10.88	7
A-6-6	12.05	10.4	6
A-7-1	12.85	11.15	7
A-7-2	11.17	10.27	6
A-7-3	13.81	11.95	7
A-7-4	11.72	10.39	6
A-7-5	14.77	10.73	8
A-7-6	12.35	10.75	7
A-7-7	12.87	10.82	7
Total number of passes (nominal)			**216 (256)**
Percentage reduction compared to 8 passes			**12**

The analysis of the possibility of reducing the number of sterile machining passes was performed based on the table top surface. It was assumed that regardless of the actual machining allowances, this surface is machined in 8 passes, 2 mm each, which results from the maximum measured machining allowance 14.77 mm. Based on the actual allowances, the number of machining passes obtainable for each table was determined. The results for the Asian foundry are presented in Table 6, and for the European foundry in Table 7.

Table 7
The number of machining passes for the table top surface from the European foundry and their possible reduction

No of casting	a_{p_max} [mm]	a_{p_min} [mm]	No of passes
E-1-1	8.62	4.69	5
E-1-2	6.83	4.71	4
E-1-3	6.99	4.71	4
E-1-4	6.31	4.48	4
E-1-5	6.69	4.13	4
E-1-6	9.54	3.68	5
E-2-1	7.69	4.89	4
E-2-2	7.97	4.53	4
E-2-3	7.36	4.88	4
E-2-4	6.86	4.47	4
E-2-5	8.46	4.44	5
E-2-6	12.54	4.92	7
E-3-1	7.52	5.34	4
E-3-2	6.34	4.63	4
E-3-3	12.79	5.17	7
E-4-1	5.84	5.19	3
E-4-2	10.05	4.64	5
E-4-3	6.16	4.39	4
Total of passes (nominal)			**81 (144)**
Percentage reduction compared to 8 passes			**44**

For castings from the Asian foundry, the potential reduction in the number of idle machining passes in a batch of 32 castings is 12%, and the European foundry in a batch of 18 castings 44%. This problem therefore becomes very apparent for various suppliers.

A similar analysis was carried out for the remaining machined surfaces of castings from both foundries. The reference number of machining passes (currently used in machining a given group of surfaces) was based on the maximum allowance in a given group of machined surfaces. The results are presented in Table 8.

Table 8
Possibilities to reduce the number of idle machining passes for the analyzed castings

SURFACE	Asian foundry	European foundry
top surface	3.75%	34.44%
pockets	30.21%	36.11%
truck surfaces	18.75%	15.28%
supporting surfaces	17.50%	14.44%
back wall	20.83%	59.26%
side walls	16.67%	54.63%
front surface	20.63%	30.33%
front nut surface	28.75%	21.11%

Conclusions

The following general conclusions can be drawn from the tests:

- castings made by the European foundry are characterized by significantly lower machining allowances (Table 2 – median of allowances),
- the repeatability of allowances on individual casting surfaces from both foundries is similar (Table 2 – standard deviation values),
- minimizing the volume of allowances by optimizing their distribution will be most effective for machined surfaces perpendicular to the Z axis – the surface of the table top accounts for 90% of them. The machined surface areas perpendicular to the X and Y directions are similar, so changing their distribution (shifting to the right or left) will not significantly reduce the total volume of allowances removed (Table 1).

It is worth noting that the cheaper Asian casting (€ 490) compared to the European casting (€ 650) has larger machining allowances. The cost of the additional material is € 45, and the increased costs of tool wear (on average 3 machining passes more for the countertop itself) € 2,6 and the cost of the machine's operating hour for additional passes for one piece € 41,1. Therefore, the actual difference in the cost of the castings of both suppliers is € 112,4 instead of € 160. Most importantly, it is possible to reduce the material cost by standardizing the allowances, and by reducing the costs of machining by the foundry and the machining plant.

Reduction of machining allowance on the table in tables made by the Asian foundry will bring savings due to lowering the cost of castings, as well as the wear of cutting inserts and the machine's working time. Annual savings (for 500 castings) will be:

- for carbide machining with a 2 mm reduction of allowance (one machining pass) € 11 673:
  - casting costs reduced by € 6105,
  - cutting insert costs down by € 434,
  - DMC200U machine costs reduced by € 5134,
- for carbide machining with an allowance of 4 mm (two machining passes) € 23 346:
  - casting costs reduced by € 12 210,
  - cutting insert costs reduced by € 868,
  - DMC200U machine costs reduced by € 10 268,
- for machining with ceramics by reducing the allowance by 2 mm (one machining pass) € 7388:
  - casting costs reduced by € 6105,
  - cutting insert costs reduced by € 323,
  - DMC200U machine costs reduced by € 960,
- for machining with ceramics by reducing the allowance by 4 mm (two machining passes) € 14 776:
  - casting costs reduced by € 12 210,
  - cutting insert costs reduced by € 646,
  - DMC200U machine costs reduced by € 1920.

Matching the number of machining passes to the actual allowance values is particularly important when the castings come from different suppliers, and therefore their machining allowances differ. Therefore, the implementation of the system of adjusting the number of machining passes will allow an additional reduction in the machine's operating costs.

The analysis also proved that the current way of fitting the casting to the reference model is not optimal – it happens that manual corrections are necessary. Matching castings on raw surfaces could solve this problem - these surfaces are usually the same in castings from various foundries, castings differ mainly in surfaces with machining allowances. Additional research is recommended.

It is reasonable to require the 3D casting model from the casting supplier. The model can be the basis for assessment of the casting and setting for machining according to a method based on the use of a 3D scanner.

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