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STUDY OF THE GEOMETRY OF GRINDING MACHINES USED FOR LARGE SCALE CRANKSHAFT MACHINING

Abstract. *In the paper, grinding process control problems that occur during the marine diesel engine crankshaft production are addressed. The large size crankshafts have a length of up to 12 m and weigh up to 25 tons, but the final grinding allowance for the diameter is ca. 0.3-0.4 mm. To achieve this, very high accuracy of the mechanical parts of the grinding machine is necessary. The study focused on the measurement of parameters such as level, linearity, parallelism, runout and coaxiality of the respective mechanical parts of the grinding machine. Based on the results, some recommendations were made on the inspection procedure in order to ensure a consisted quality of the produced crankshafts. The obtained roughness parameters after grinding were found highly satisfactory, allowing effective polishing afterwards.*

Keywords: *crankshaft; grinding; roughness; runout; linearity; parallelism*.

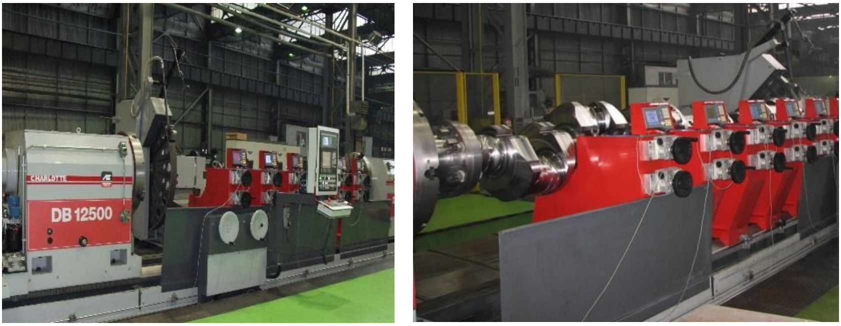
1. INTRODUCTION

The crankshaft is a crucial element of the marine engine, and special standards prescribe how they must be projected, e.g. the one issued by PRS Executive Board [1]. Its failure may threaten the life of the shipboard personnel and passengers, so there is a need to continually improve the technology, quality control, and the inspection of the machine tools' performance. Nowadays, there are three main technologies for large marine diesel engine crankshaft fabrication, which produce assembled crankshafts, semi-built crankshafts and fully forged ones [2]. The first two technologies have crankshaft parts that joined together with the shrink-fitting method [3]. A critical step in the manufacture of forged crankshafts is the grinding of its sidewalls by applying several strategies, e.g. axial plunge grinding, axial face grinding, and multi-step axial face grinding [4]. The rising demands on quality also force the improvement of grinding performance and are driving the development of machines for grinding [5]. Grinding parameters have direct impact on the integrity of machined surfaces and their characteristics, such as residual stresses, surface roughness and dimensional stability [6]. Improper grinding was reported to be a source of misalignments in journals, high stress concentration, and high surface roughness [7]. Shen et al. [8] examined the elastic deformations of the large size crankshafts generated by grinding process, while Torims et al. [9] analyzed the influence of grinding parameters on the surface texture formation in the reparation process of marine diesel engine crankshafts. Hashimoto et al. pointed out that the improvements aimed to achieve fuel efficiency raise additional demands on the superfinishing of the crankshafts [10]. Importance of the cooling conditions was analyzed by Maruda et al. [11]. Tian et al. [12] proposed a portable power monitoring system for grinding process.

The customer sets very high demands on the surface topography with $Ra < 0.3$ µm, which is almost impossible to obtain with the grinding technology. Therefore, hand polishing is applied after grinding. Typically achievable *Ra* parameters after grinding are between 0.5 and 1.4 µm, while after polishing it lays between 0.1 and 0.3 µm [13]. However, hand polishing has very limited impact on the surface, so the grinding process has to prepare the surface as efficiently as possible. The study below is dedicated to the grinding process of the crankshaft machining, as well as the inspection procedures aimed to control the performance of the grinding machine.

2. MATERIALS AND METHODS

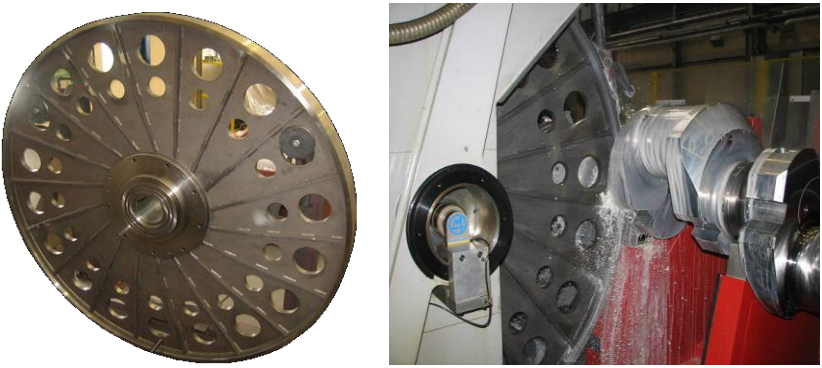
Grinding is one of the final machining processes of the crankshaft fabrication. Main journals and cranks obtain the dimensions close to the upper tolerance, so that the surface can be finished by hand (lapping and polishing procedures). The examined grinding process was performed with a grinder DB12500 type (Figure 1) equipped with the control system Sinumerik 840D, measurement system MARPOSS and eccentric machining system PENDULUM.



(a) (b)

Figure 1 – The grinding machine DB12500 type:
(a) overall view; (b) the crankshaft ready for being grinded

The grinding tool was the disc-type grinding wheel MOLEMAB B126-100639 S.630090 shown in the Figure 2. Its diameter was ø2000 mm, and width B = 140 mm, and it was covered with the cubic-form boron nitride (c-BN). The use of large-diameter grinding wheels with abrasives of the highest hardness (diamond, cubic boron nitride) in various tasks of precise shaping makes it possible to carry out preliminary and final grinding of operationally responsible external surfaces in one processing cycle, due to the increased durability of the tool in the technologically correctly built cycle, for example, when grinding rolls of rolling mills after surfacing with wear-resistant wire material [14]. The maximal cutting velocity and rotational speed were $V_{\max}$ = 50 m/s and $n_{\max}$ = 473 rpm, respectively.



(a) (b)

Figure 2 – The grinding wheel MOLEMAB B126-100639 S.630090 type:
(a) overall view; (b) during the operation

Like in any machining technology, the final surface quality was dependent on the geometry and performance of the “machine – tool – workpiece” system. For any type of fabricated crankshaft, the grinding operations sequence has been assumed to be the same, namely, the main journals were to be grinded first (main axis of the crankshaft), so the final dimensions were achieved, and then the crank-pins were grinded. In general, the grinding process can be described as follows:

- The grinding allowances of the diameter were ca. 1 mm, maximally up to 1.5 mm. It was more desirable to leave larger allowances on the crank-pins, in order to avoid the increased uncertainty when the angle of the reference crank-pin was measured.

- After initial grinding of all the main journals, the fine grinding was initiated.
- The allowance for the fine grinding was ca. 0.3-0.4 mm on diameter.
- Supporting tailstocks are always put down under the grinded main journal. After grinding, the journal is again supported, and the position of the crankshaft is corrected on the base of flexometer indications.
- High pressure washing of the grinding disc after each operation is performed in order to prolong durability of the tool.

The above procedure is presented schematically in Figure 3. It is crucial that, after the initial grinding of all the main journals, MAROPSS device measurements are processed by and form corrections are performed, so that final grinding commences only after the main axis accuracy is assured.

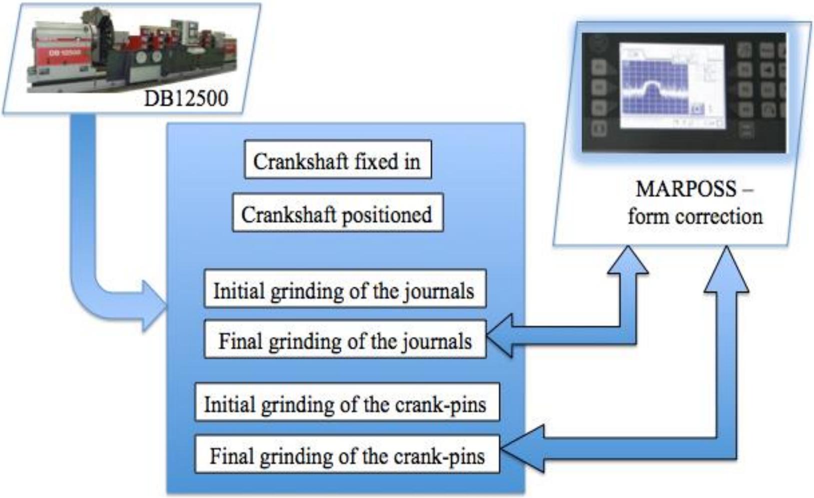


Figure 3 – Crankshaft grinding procedure

The grinding machine DB12500 is equipped with the measurement system MARPOSS, which consists of three main units:

- Automatic system MARPOSS WHEEL BALANCING designed to continually supervise the balance of the grinding disc while it is in motion.
- The main measurement system MARPOSS POST-PROCESS designed to measure form deviations of the main journals and crank-pins. The unit has three supporting points and the specially constructed arm, FENAR-L, which enables the measurement of both main journals and crank-pins. The

sensor collects 3600 points per rotation and is synchronized with the control system SINUMERIK 840D. The measured values are averaged down to 360 points using one of the delivered algorithms. These points are the basis for the form compensation table correlated with the angle position of the measured pivot. The form correction is performed using the perpendicular support with defined virtual axis. Resolution of the device is 0.001 mm.

- The third unit is a MARPOSS MONITORING equipped with the ultrasonic microphones. It is designed to monitor the slot between grinding disc and grinded material (the GAP function) in order to control the contact between the tool and the ground material.

In order to maintain the consistent performance of the grinding machine, it was checked regularly with additional devices. Figure 4 presents the electronic level LE051 type produced by MICROPLAN. It is equipped with a digital/analog display, and its internal mechanism is submerged in an oil-bath box. Achievable sensitivity of the level LE051 is 1 µm/m or 0.2 second of arc. It has 5 measuring scales providing resolutions from 250 µm/m per division down to 1 µm/m per division. The data can be transferred to a PC through the serial connections RS-232.

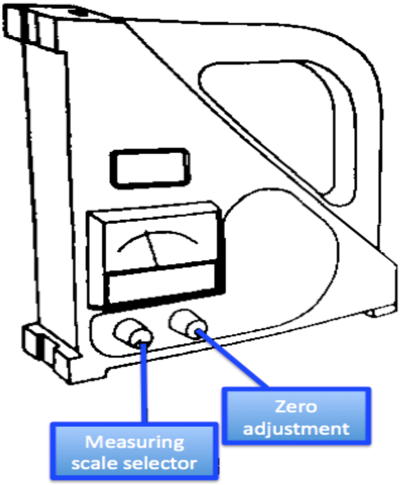
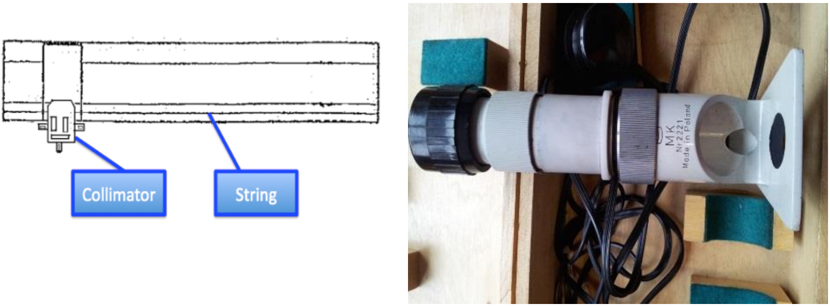


Figure 4 – The electronic level LE051 type

Linearity of the bed with the fixed headstocks of the grinding machine was inspected using the collimator device with a string and measuring magnifier, presented in Figure 5.

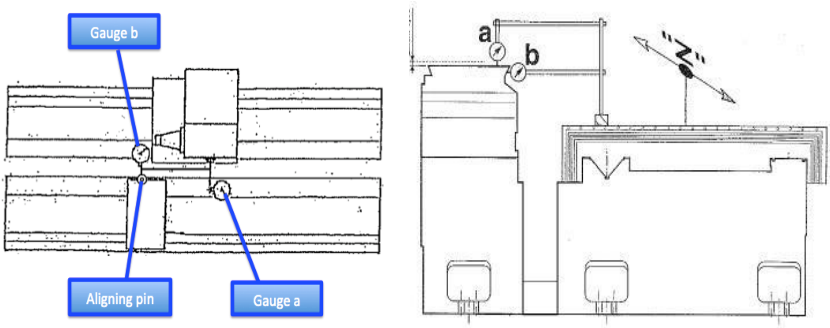


(a)

(b)

Figure 5 – The linearity measurement of the bed:
(a) overall scheme; (b) measuring magnifier

Moreover, the parallelism of the bed with fixed headstocks and the support was inspected. In the measurement, the electronic dial gauges (produced by Kordt) were used, with a resolution of 0.001 mm. They were placed on the grinding machine support and bed as illustrated in Figure 6.



(a)

(b)

Figure 6 – The parallelism measurement:
(a) view from the top; (b) side view

Similar electronic dial gauges were used in the measurement of the grinding disc runout as well as of the fixed headstocks. In the latter case, both radial and axial runout was measured. Additionally, the following parameters were inspected:

- parallelism between the axes of the disc cone during the headstock movement,
- distance between the vertical positions of the disc and headstock axes,
- runout of the disc cone,
- and the coaxiality of the fixed headstocks.

Since the roughness of the crankshaft surface is a very important parameter obtained after grinding, it was also measured. On-machine and in-process surface metrology is important for quality control in manufacturing of precision surfaces [15].

According to the documentation, the main journals must have a very smooth surface with $Ra < 0.3$ μm, so the grinding prepares the surface leaving only little deformation that can easily be removed during polishing. After grinding, the Ra parameter was measured with the portable surface roughness tester Surftest SJ-201P. It was chosen because of the obvious difficulty with applying the stationary profilometer to a huge detail such as the crankshaft 18W46 type. The most important parameters of SJ-201P device are as follows:

- measuring range 350 μm (from -200 to +150 μm),
- diamond stylus tip of radius 5 μm,
- sampling length 0.25 mm, 0.8 mm, 2.5 mm,
- displaying range from 0.01 μm to 100 μm,
- resolution is dependent on the measuring range, with the highest being 0.01 μm/10 μm,
- data output via RS-232 interface unit.

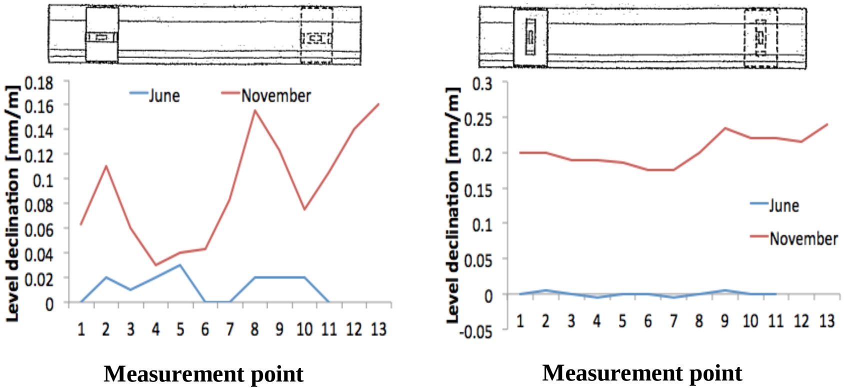
As such, this device was considered sufficient to inspect the roughness of the crankshaft surface both after grinding and later, after hand polishing.

3. RESULTS AND DISCUSSION

The inspection of the abovementioned parameters was performed in June and again 5 months later, in November. The results are presented and discussed in the respective subsections below.

3.1. Level declinations

Figure 7 presents the results of level measurements obtained at different measuring points along the bed with fixed headstocks, in June and in November. The measurement was performed both in parallel and perpendicular directions.



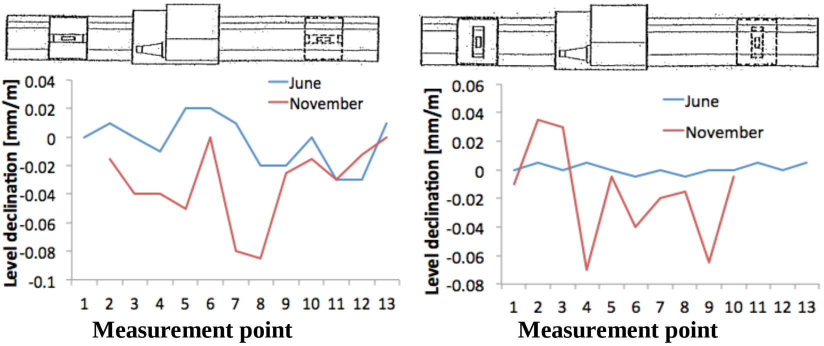
(a) (b)

Figure 7 – Level check of the bed with fixed headstocks:
(a) parallel; (b) perpendicular

The general observation is that after 5 months, the level deteriorated, so its regulation was needed to avoid the dimensional errors in the grinding process. Moreover, it is seen that the dispersion of the results is larger in the parallel direction (between 0 and 0.03 mm/m in June and between 0.03 and 0.16 mm/m in November) than in the perpendicular measurement (between -0.005 and 0.005 mm/m in June and between 0.175 and 0.24 mm/m in November). However, the dispersion of the respective results obtained both in the parallel and perpendicular directions was smaller in June than in November. It was concluded that the most instable level was the parallel direction, therefore it was recommended to check it more frequently, with the measurement taken at a minimum 3 points, to check for any trend.

Similarly, the bed level declination was checked along the *z* axis, both in the parallel and perpendicular directions. Figure 8 shows the positioning of the electronic level and the results of the measurement.

Again, the parallel direction displays a larger dispersion, particularly in the June measurements. The November measurement results are biased towards the negative values and are more dispersed than those of June. Thus, it can be recommended that the *z*-axis level is checked and corrected more often, and the measurement should be performed at all 13 measuring points.

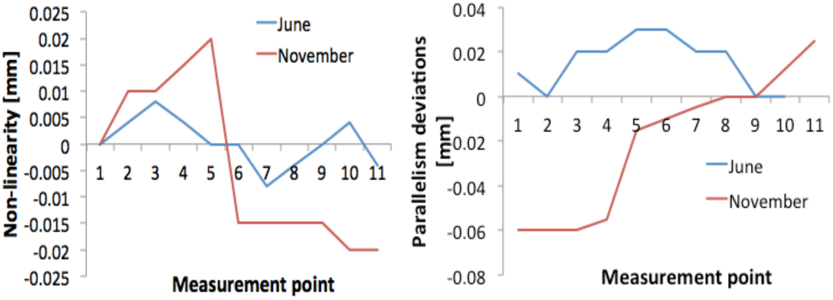


(a) (b)

Figure 8 – Level check of the bed in the *z* axis:
(a) parallel; (b) perpendicular

3.2. Linearity and parallelism deviations

The measurement results for the linearity of the bed with fixed headstocks are presented in Figure 9a. On the other hand, Figure 9b presents the results of the parallelism measurement between the bed and the support. The measurements were performed at 11 points distanced ca. 1 m apart, and each point was given a subsequent number.



(a) (b)

Figure 9 – The measurement results for the bed with the fixed headstocks:
(a) linearity and (b) parallelism between the bed and the support

It should be noted that the linearity measurement in June revealed deviations between -0.01 and 0.01 mm, while in November twice as larger, namely, between -0.02 and 0.02 mm. Nevertheless, the latter is still acceptable, since the permissible non-linearity of the bed with the fixed headstocks is 0.02 mm per 1000 mm, but the obtained results indicated immediate need of correction. It was also observed that the right part of the bed (points from 1 to 5) tended to reveal positive values of non-linearity, while negative values dominate in the left part.

In the case of parallelism deviations, the trend is clear and a correction of the mutual position of the bed and support can easily be made.

3.3. Other results for the grinding machine

The results of other measurements are shown in Table 1.

Table 1 – Measurement results for various features of the grinding machine

<table>
<tr><th>Measured feature</th><th colspan="3">Measurement result</th><th>Permissible error</th></tr>
<tr><td>Grinding disc perpendicularity [mm/mm]</td><td>point A
0.01/400</td><td>point B
0.015/300</td><td>point C
0.02/600</td><td>0.02/300</td></tr>
<tr><td>Headstock S2 runout [mm/mm]</td><td>point A
0.025/350</td><td colspan="2">point B
0.01/300</td><td>0.025/300</td></tr>
<tr><td>Headstock S1 runout [mm/mm]</td><td>point A
0.01/350</td><td colspan="2">point B
0.025/350</td><td>0.025/300</td></tr>
<tr><td>Disc cone coaxiality [mm/mm]</td><td>point A
0.007/300</td><td colspan="2">point B
0.02/300</td><td>0.03/300</td></tr>
<tr><td>Vertical position of the disc and headstock axes [mm/mm]</td><td colspan="3">0.25/920</td><td>0.4/1000</td></tr>
<tr><td>Disc cone runout [mm]</td><td>point A
0.002</td><td colspan="2">point B
0.001</td><td>0.005</td></tr>
<tr><td>Headstocks coaxiality [mm]</td><td>point A
0.01</td><td colspan="2">point B
0.02</td><td>0.02</td></tr>
</table>

The presented results proved the proper performance of the grinding machine. In some cases, where the values approached the permissible error, it indicated the need for calibration of the machinery. Since the quality control of the produced crankshafts confirmed the final form and dimension tolerances obtained, the inspection procedure of the grinding machine geometry was deemed satisfactory with the addition of the improvement recommendations discussed above.

3.4. Roughness after grinding

The examples of the roughness measurement results after grinding are shown in the Tables 2 and 3. Main journals were marked CG with subsequent number, while crank pivots were marked CK with subsequent number.

The results are highly satisfactory, so that the final roughness below *Ra* = 0.3 μm is easily achievable through hand polishing.

Table 2 – Roughness measurement results [μm] for the main journals CG after grinding

Journal number	Point 1	Point 2	Point 3	Point 4
CG1	0.36	0.40	0.33	0.31
CG2	0.32	0.36	0.41	0.35
CG3	0.28	0.32	0.39	0.34
CG4	0.31	0.36	0.33	0.32
CG5	0.31	0.36	0.39	0.33
CG6	0.28	0.38	0.29	0.35
CG7	0.36	0.40	0.41	0.40
CG8	0.32	0.36	0.40	0.38
CG9	0.28	0.38	0.35	0.30
CG10	0.41	0.35	0.32	0.43

Table 3 – Roughness measurement results [μm] for the crank pivots CK after grinding

Pivot number	Point 1	Point 2	Point 3	Point 4
CK1	0.36	0.34	0.32	0.31
CK2	0.29	0.38	0.38	0.38
CK3	0.34	0.32	0.34	0.36
CK4	0.36	0.34	0.29	0.34
CK5	0.37	0.28	0.38	0.33
CK6	0.39	0.27	0.28	0.30
CK7	0.37	0.39	0.34	0.28
CK8	0.25	0.34	0.41	0.40
CK9	0.31	0.45	0.38	0.34

4. CONCLUSIONS

The presented study aimed to evaluate the inspection procedure of the grinding machine involved in the marine diesel engine crankshaft production process. It was found that the most instable parameter was the level of the bed with fixed headstocks in the parallel direction. Based on this finding, it is recommended to monitor the fixed heastocks' bed level in shorter intervals, e.g. every 3 months, not necessarily comprehensively, but with measurements taken at a minimum of 3 points to check the trend. Additionally, it was recommended that the *z*-axis level is checked and corrected at least every 3 months, and the measurement should be performed at all 13 measuring points. Measured linearity of the bed with the fixed headstocks revealed an immediate need for correction, no such correction of the inspection procedure was considered necessary. Under the above conditions, the roughness obtained after grinding was fond to be highly satisfactory.

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References: **1.** PRS Executive Board: (2007) Calculation of crankshafts for diesel engines: Rules. Gdansk: Polski Rejestr Statkow; Poland, ISBN 978-83-60629-27-7. **2.** *Fonte, M., Duarte, P., Anes, V., Freitas, M., Reis, L.*: (2015) On the assessment of fatigue life of marine diesel engine crankshafts. Eng Fail Anal, 56: 51-57, DOI 10.1016/j.engfailanal.2015.04.014. **3.** *Siemiatkowski, Z.*: (2017) Experimental evaluation of the shrink-fitted joints in the assembled crankshafts. Journal of Engineering Technology, 6: 832-841. **4.** *Oliveira, J. F. G., Silva, E. J., Gomes, J. J. F., Klocke, F., Friedrich, D.*: (2005) Analysis of grinding strategies applied to crankshaft manufacturing. CIRP Annals, 54: 269-272, DOI 10.1016/S0007-8506(07)60100-0. **5.** *Oliveira, J. F. G., Silva, E. J.; Guo, C.; Hashimoto, F.*: (2009) Industrial challenges in grinding. CIRP Annals, 58: 663-680, DOI 10.1016/j.cirp.2009.09.006. **6.** *Thanedar, A., Dongre, G. G., Singh, R., Joshi, S. S.*: (2017) Surface integrity investigation including grinding burns using barkhausen noise (BNA). Journal of Manufacturing Processes, 30: 226-240, DOI: 10.1016/j.jmapro.2017.09.026. **7.** *Silva, F. S.*: (2003) An investigation into the mechanism of a crankshaft failure. Key Engineering Materials, 245-246: 351-358, DOI 10.4028/www.scientific.net/KEM.245-246.351. **8**. *Shen, N. Y., Li, J., Wang, X., Ye, J., Yu, Zh.*: (2014) Analysis and detection of elastic deformation of the large-scale crankshaft in non-circular grinding. Applied Mechanics and Materials, 532: 285-290, DOI 10.4028/www.scientific.net/AMM.532.285. **9.** *Torims, T., Vilcans, J., Zarins, M., Brutans, V., Ratkus, A.*: (2012) A Study on how Grinding Technology Parameters Affect the Surface Texture Formation of Marine Diesel Engine Crankshafts. Advanced Materials Research, 538-541: 1413-1421, DOI 10.4028/www.scientific.net/AMR.538-541.1413.148. **10.** *Hashimoto, F., Yamaguchi, H., Krajnik, P., Wegener, K., Chaudhari, R., Hoffmeister, H. W., Kuster, F.*: (2016) Abrasive fine-finishing technology. CIRP Annals, 65: 597-620, DOI 10.1016/j.cirp.2016.06.003. **11.** *Maruda, R., Legutko, S., Krolczyk, G., Raos, P.*: (2015) Influence of cooling conditions on the machining process under MQCL and MQL conditions. Tehnicki Vjesnik – Technical Gazette, 22: 965-970, DOI: 10.17559/TV-20140919143415. **12.** *Tian, Y. B., Liu, F., Wang, Y., Wu, H.*: (2017) Development of portable power monitoring system and grinding analytical tool. Journal of Manufacturing Processes, 27: 188-197, DOI: 10.1016/j.jmapro.2017.05.002. **13.** *Grzesik, W.*: (2015) Effect of the machine parts surface topography features on the machine service. Mechanik, 8-9: 587-593, DOI 10.17814/mechanik.2015.8-9.493 (In Polish). **14.** *Gutsalenko, Yu. G., Gutsalenko, O. G., Burenkov, M. V., Shelkovoy, A. M.*: (2002) Electroerosive treatment of surfacing on roll grinding machines: special equipment, tools, organization of production (Prospect of scientific and technical development: VII International Exhibition “Metalworking 2002”, May 27-31, 2002, Moscow). Kharkiv, NTU “KhPI”; p.: 4 (In Russian). **15.** *Gao, W., Haitjema, H., Fang, F. Z.; Leach, R. K.; Linares J. M.*: (2019) On-machine and in-process surface metrology for precision manufacturing. CIRP Annals, Article on press, Available online 13 June 2019, DOI 10.1016/j.cirp.2019.05.005.

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ВИВЧЕННЯ ГЕОМЕТРІЇ ШЛІФУВАЛЬНИХ ВЕРСТАТІВ, ЯКІ ВИКОРИСТОВУЮТЬСЯ ДЛЯ ОБРОБКИ ВЕЛИКОГАБАРИТНИХ КОЛІНЧАСТИХ ВАЛІВ

Анотація. У *статті розглядаються проблеми управління процесом шліфування, що виникають при виробництві колінчастого вала суднового дизеля. Колінчасті вали великого розміру мають довжину до 12 м і важать до 25 тонн, але допуск на остаточне шліфування для діаметра становить 0,3-0,4 мм. Для цього необхідна дуже висока точність механічних деталей шліфувального верстата. Дослідження було зосереджено на вимірі таких параметрів, як площинність, лінійність, паралельність, биття і співвісність відповідальних за вихідну точність механічних частин шліфувального верстата. Робота виконана зі шліфувальним верстатом типу DB12500, оснащеним системою управління Sinumerik 840D, а також системами вимірювання та ексцентричної обробки. На підставі отриманих результатів були зроблені деякі рекомендації по процедурі перевірки з метою забезпечення стабільної якості випуску колінчастих валів. Шліфувальним інструментом був шліфувальний круг дискового типу MOLEMAB B126-100639 S.630090. Вибір хімічно інертного до оброблюваного матеріалу з вмістом вуглецю і водночас особливо твердого абразивного інструментального матеріалу (c-BN), а також значна протяжність робочої частини шліфувального круга по периферії (понад 6 м), є важливою передумовою забезпечення стійкості інструменту в циклі продуктивної і якісної зовнішньої обробки заданих функціональних поверхонь розглянутих великогабаритних колінчастих валів. Припуски на обробку розподілялися між попереднім і чистовим переходами шліфування з деяким збільшенням (резервуванням забезпечення точності) для шатунних шийок, обробка яких велася другим планом. Мікрогеометричну якість поверхні контролювали за допомогою портативного вимірювача шорсткості поверхні Surftest SJ-201P, що дозволило уникнути очевидних проблем вимірювання профілю в задачах контролю великогабаритних деталей складної ступінчастої форми, якими є суднові колінчаті вали. Отримані параметри шорсткості після шліфування (Ra≤0,4 мкм) були визнані вагомою мірою задовільними, що дозволило після цього ефективно полірувати до необхідного за основними функціональними поверхнями рівня Ra 0,3 мкм.*

Ключові слова: *колінчастий вал; шліфування; шорсткість; биття; лінійність; паралельність.*