Remarks on the Automatic Cylinder Oil Mixing System for Two Stroke Dual Fuel Crosshead Marine Engines

doi: 10.2478/mape-2020-0002

MAPE 2020, volume 3, issue 1, pp. 13-27

Date of submission to the Editor: 03/2020
Date of acceptance by the Editor: 06/2020

Włodzimierz Markiewicz
ORCID ID: 0000-0002-2283-3375
BP plc, United Kingdom

INTRODUCTION
Commissioning and operation of first two stroke, dual fuel (Diesel Cycle) engines is one of the most important part of the marine engine rooms operation (Nozdrzykowski, 2006, 2018; Nozdrzykowski and Bejger, 2013; Nozdrzykowski and Janecki, 2014; Nozdrzykowski, Grządziel and Harušinec, 2018; Nozdrzykowski and Chybowski, 2019). It revealed whole gamut of new problems that presented operators with potential for increased wear of the liners, piston rings and pistons (Gawdzińska, Chybowski and Przetakiewicz, 2017; Gawdzińska et al., 2018, 2019) which is directly related to type of fuel used and its Sulphur content (Antturi et al., 2016; Chu Van et al., 2019; Wang, Zhang and Gan, 2019). Sulphur is neutralized with, available commercially from 1950's, high alkalinity cylinder oils. Problems arise during fuel changeover, which also requires change of cylinder lubricating oil base number (CLO BN). Sulphur limit in marine fuels has been introduced with MARPOL Annex VI – Fuel Sulphur Limits (Fig. 1).

Source: (MAN Diesel & Turbo, 2018)
Geographically, it is defined by boundaries of vessel operations which are called Sulphur Emission Control Area (SECA) (Laskowski, Chybowski and Gawdzińska, 2015; Chybowski et al., 2016). Location of this areas is presented in Figure 2. Further, final change to the Sulphur cap has been introduced at 1st of January 2020, where maximum Sulphur content in marine fuel was reduced from 3.5% to 0.5%

Fig. 2 SECA + NECA
Source: (MAN B&W Diesel A/S, 2013)

CAUSES AND EFFECTS OF INCORRECT CLO DOSING
Cylinder liner damage or increased wear has its source in either under or over lubrication. Correct dosing depends on amount of Sulphur in the fuel oil as well as engine load (including power optimisation in the form of Exhaust Gas Bypass and Turbocharger cut out. This in turn sets the required amount of alkali additives (Fig. 3).

Fig. 3 Liner Lubrication
Source: (MAN B&W Diesel A/S, 2013)
Base Number (BN) is a measure of oil’s ability to neutralise sulphuric acid on the cylinder liner surface. Corrosion has to be controlled and is extremely important in the tribology required to establish and retain oil film on the surface of the liner. With too much BN and subsequently over neutralisation, surface of the liner will be polished, which will result in disruption to the friction and increased risk of damage to liner surface and piston rings (Fig. 4). Too low BN value will result in insufficient neutralisation and significant risk of low temperature sulphur-based corrosion.

![Fig. 4 Open (L) and closed (R) structure of the liner surface](source: (MAN Diesel & Turbo, 2018))

Sulphuric acid is being produced during combustion of fuels containing sulphur. It may liquefy on the liner surface – this is due to presence of water in the scavenge air and thermodynamics of combustion, when temperature and pressure creates atmosphere which is below dew point of SO₃ (Fig. 5).

![Fig. 5 Conversion of S to H₂SO₄](source: (MAN Diesel & Turbo, 2018))

With inadequate neutralisation, level of iron in the cylinder oil will increase. According to MAN Diesel & Turbo, level of 200 mg/Kg corresponds to nominal wear of the cylinder liner and equals 0.1 mm/1000 Running Hours (RH) (Fig. 3). Therefore, higher values will indicate increased wear of the liners, rings and ultimately pistons.

Total amount of the alkali additives must correspond to the Sulphur content according to the equation below:

\[
BN = FRF \times S\%
\]

where:
FRF for CLO BN100 (high BN, liquid fuel) = 0.40 g/kWhS%
And for CLO BN40 (low BN, methane fuel) – 0.25 g/kWhS%.
MAN sets the minimum specific CLO feedrate at 0.6 g/kWh, which will be achieved with fuel that contains 1.15% of sulphur, using CLO BN100. This sets the theoretical limit for use of BN100 CLO at 1.15%S.

With use of CLO BN40 (utilised during methane operations) 0.6 g/kWh limit does not allow for BN – S equilibrium (Fig. 6).

![Fig. 6 ACC Area (feed rate factor) for CLO BN100 used in Mark 8-8.1 and newer engines](source)

Source: (MAN Diesel & Turbo, 2015)

MEGI engines cannot be run in gas mode at low loads (≤ 20). This is due to physical size of the fuel injectors, which also serve as pilot ones.

It is therefore obvious that operation of the engine with low sulphur fuel will be much more complicated due to relationship between liner surface corrosion and its resistance to friction wear and also between BN of the CLO, its detergency and possible surplus of the alkali additives. (Chybowski, Laskowski and Gawdzińska, 2015)

To precisely determine scale of the neutralisation process and therefore the physical and chemical attributes of used CLO, oil must be removed from the engine during Sweep Test (Fig. 7). Test is being carried out by sampling cylinder drains at predefined time and at various specific feed rates.

![Fig. 7 Sweep Test](source)

Source: (MAN Diesel & Turbo, 2018)
Measuring iron and residual BN contents will allow for a very precise assessment of the liner condition as well as need of adjustment to feed rate if required to move back in to safe area (Fig. 8). It must be noted, that Sweep Test should only be carried out with fuels that contain higher amounts of Sulphur. Otherwise, results may not be precise enough, or much longer time will be required to complete the test. Operator, should also ensure that engine load is relatively steady during the test.

![Fig. 8 Cylinder Oil Flow](source)

Insufficient lubrication (underlubrication), invariably leads to excessive wear / damage both to surface of the cylinder liner as well as piston rings, due to increased corrosion and lower overall detergency of the cylinder oil being admited to the unit. Cold corrosion becomes reality and is likely to happen. Engine is in danger of underlubrication in high load band only, this is due to activation of LCD at loads below 25% of MCR. Operating LCD increases CLO feedrate by 25% and thus protects running gear from underlubrication.

Too much cylinder oil will lead to overlubrication, which in time will cause for surface structure to close (Fig. 8) and subsequenty occurence of bore polishing. Noted will be increased amount of unused alkali additives, which may cause problems with Tier III equipment further down the line. For example, operation of the engine EGR system will be affected due to need for removal of alkali solids and lack of pH equilibrium in the primary (air cooler – buffer tank) circuit.

**INCORRECT LUBRICATION PREVENTION**

Based on the above rationale, it becomes apparant that there is a need for use of two cylinder oils, differentiated by Base Number (BN).

Point of switch is based solely on the experience gained during first days and weeks after the delivery (Fig. 9).
Sweep Test will allow for correct setting of the FRF for high sulphur fuel and frequent, detailed scavenge space inspections will provide experience required to establish correct BN for use with methane fuel.

**Automatic Cylinder Oil Mixing (ACOM)**
ACOM is the newest solution currently in use with MEGI Power Plants (Fig. 10). System allows for cylinder oil mixing and dosing in relation to engine load and type of fuel used.

ACOM also allows for dosing engines operating in specific dual fuel mode (SDF) – which defines relationship between pilot and gas fuel. It is a very important feature of the MEGI engine and utilised when engines are part of the tank pressure control and / or when plant is being operated with heel. ACOM mixes two, different BN, oils into the one with requested BN value. Currently BN 100 and BN16 are utilised as a base oils. This creates a very ‘flexible’ environment, where all the currently used BN values (including exotic ones) are available. ACOM is controlled with the engine ECS (Fig. 11) allowing for it’s continuous
monitoring. All the adjustments can be carried out through MOP and/or ACOM digital panel. Hardware itself is of quite small footprint and consists of relatively small number of parts.

![Automated Cylinder Oil Mixing Unit on the skid](source)

**Fig. 11 Automated Cylinder Oil Mixing Unit on the skid**
Source: (MAN Diesel & Turbo, 2018)

Figure 12 describes typical ACOM control panel in the MOP. It consists of functions as per below:

- High BN Value – BN value setting for high Sulphur fuel.
- Low BN Value – BN value setting for low Sulphur/gas fuel.
- Feed Rate Factor – value obtained during the Sweep Test.
- Engine Mean Effective Pressure given in percent at which LCD algorithm changes in to RPM mode.
- Minimum feedrate – minimum, specific CLO dose delivered to the engine in the RPM algorithm band.

Therefore, the biggest challenge faced by the operator will be to ensure CLO contains correct amount of BN additives when engine is being operated with low sulphur fuel. Let's assume that:

- Engine operates in HFO mode with liquid fuel consisting of 1.8% of Sulphur.
- ACC Feed rate factor = 0.25 g/kWh x S% (established during sweep test).
- Minimal specific CLO feedrate = 0.6 g/kWh, therefore:

  calculated minimal specific CLO feedrate = 0.25 x 1.8 = 0.45 g/kWh.

Value of 0.45 g/kWh is below minimal feedrate. ECS therefore will request 0.6 g/kWh. Sulphuric acid may be then completely neutralised, increasing risk of bore polishing and thus increased wear.
Therefore, the biggest challenge faced by the operator will be to ensure CLO contain correct amount of BN additives when engine is being operated with low sulphur fuel.

Let's assume that: Engine operates in HFO mode with liquid fuel consisting of 1.8% of Sulphur.

ACC Feed rate factor = 0.25 g/kWh x S% (established during sweep test)

Minimal specific CLO feedrate = 0.6 g/kWh,

therefore:

calculated minimal specific CLO feedrate = 0.25 x 1.8 = 0.45 g/kWh.

Value of 0.45 g/kWh is below minimal feedrate. ECS therefore will request 0.6 g/kWh. Sulphuric acid may be then completely neutralised, increasing risk of bore polishing and thus increased wear.

Correct dose will call for oil with reduced Base Number.

Therefore:

Minimum Feed rate/fuel S% = FRF

0.6/1.8 = 0.33 (optimal FRF)

FRF for BN 100 = 0.25.

FRF100 = FRF70 x $\frac{70}{100}$ → FRF100 = FRFop x $\frac{BNop}{100}$ → BNop = $\frac{FRF100}{FRFop}$ x 100

Optimal BN for FRF 0.33 equals to

$\frac{0.25}{0.33}$ x 100 = 76BN

Setting of 76BN will allow for correct dosing at minimal feedrate of 0.6 g/kWh.
MATERIALS AND METHODS
Feed rate factor has been established through sweep test carried out on MAN-B&W/5G70ME-C9.5-GI engine operating on HFO with Sulphur content of 2.97%. Test has taken place over five days and was carried out under conditions as laid in MAN SL2014-587:
- Engines loaded above the LCD breakpoint
- Running in Mode off
- Feed Rate Adjust Factor = 1.00
- Feed Rate set to:
  - 1.38 g/kWh for first sweep
  - 1.24 g/kWh for second sweep
  - 1.00 g/kWh for third sweep
  - 0.87 g/kWh for fourth one and
  - 0.64 g/kWh for the fifth.

ACC factor has been established according to the formula below:

\[
\text{ACC} = \frac{g}{kWh \times S\%} = \frac{\text{Feed rate}[g/kWh]}{\text{Fuel Sulph [S%]}}
\]

RESULTS AND DISCUSSION
Data had been referenced to engine running hours, engine load and elemental analysis carried out on collected samples (Table 1, 2, 3, 4, 5). Note cylinder unit No. 2 which drain was found blocked on 18th of November. Below values were obtained:
- Correction for system oil dilution
  - corrected
  - not corrected

Table 1 Sweep Test Results FR 1.38 g/kWh, Castrol Caremax Cylinder Oil Monitor

| CYLINDER UNIT | 1 | 2 | 3 | 4 | 5 |
|---------------|---|---|---|---|---|
| PISTON HOURS SINCE OVH | 560 | 560 | 560 | 560 | 560 |
| CYLINDER OIL FEED RATE | 1.38 | 1.38 | 1.38 | 1.38 | 1.38 |
| CYLINDER OIL | CYLTECH 100 |

| CYLINDER OIL | CYLTECH 100 |
|---------------|--------------|
| ■ DURING SAMPLING % MCR | 75.7 |
| % S in Fuel | 2.97 |
| Load (kW) | 10200 |
| Engine Hours | 570 |
| Feed rate | 1.38 |

The analysis results, based on the tests performed, indicate that an overall satisfactory condition for all units. There is a high BN reserve across all units. Cu content across all units is likely to reflect the running in of the Alucoat piston rings.
### Table 2 Sweep Test Results FR 1.22 g/kWh, Castrol Caremax Cylinder Oil Monitor

| CYLINDER UNIT | N° | 1 | 2 | 3 | 4 | 5 |
|---------------|----|---|---|---|---|---|
| PISTON HOURS SINCE O VH | h | 590 | 590 | 590 | 590 | 590 |
| CYLINDER OIL FEED RATE | g/kWh | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 |
| CYLINDER OIL | CYLTECH 100 |

| Date Sample Taken | 15.11.18 | 15.11.18 | 15.11.18 | 15.11.18 |
|-------------------|----------|----------|----------|----------|
| % S in Fuel | 64.3 | 63.7 | 64.2 | 64.1 | 63.3 |
| Load (kW) | 2.97 | 2.97 | 2.97 | 2.97 | 2.97 |
| Engine Hours | 589 | 589 | 589 | 589 | 589 |
| Feed rate | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 |

The analysis results, based on the tests performed, indicate an increase in Fe content on some cylinder units suggesting oil feed rate could be below optimal settings for certain combinations of fuel specification / engine load.

### Table 3 Sweep Test Results FR 0.97 g/kWh, Castrol Caremax Cylinder Oil Monitor

| CYLINDER UNIT | N° | 1 | 2 | 3 | 4 | 5 |
|---------------|----|---|---|---|---|---|
| PISTON HOURS SINCE O VH | h | 613 | 613 | 613 | 613 | 613 |
| CYLINDER OIL FEED RATE | g/kWh | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| CYLINDER OIL | CYLTECH 100 |

| Date Sample Taken | 16.11.18 | 16.11.18 | 16.11.18 | 16.11.18 |
|-------------------|----------|----------|----------|----------|
| % S in Fuel | 28.4 | 31.4 | 31.7 | 32 | 32 |
| Load (kW) | 2.97 | 2.97 | 2.97 | 2.97 | 2.97 |
| Engine Hours | 613 | 613 | 613 | 613 | 613 |
| Feed rate | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |

The analysis results, based on the tests performed, indicate a significant increase in Fe content across all cylinder units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load.

### Table 4 Sweep Test Results FR 0.86 g/kWh, Castrol Caremax Cylinder Oil Monitor

| CYLINDER UNIT | N° | 1 | 2 | 3 | 4 | 5 |
|---------------|----|---|---|---|---|---|
| PISTON HOURS SINCE O VH | h | 613 | 613 | 613 | 613 | 613 |
| CYLINDER OIL FEED RATE | g/kWh | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| CYLINDER OIL | CYLTECH 100 |

| Date Sample Taken | 17.11.18 | 17.11.18 | 17.11.18 | 17.11.18 | 17.11.18 |
|-------------------|----------|----------|----------|----------|----------|
| % S in Fuel | 15.4 | 19.5 | 17 | 20.6 | 20.6 |
| Load (kW) | 2.97 | 2.97 | 2.97 | 2.97 | 2.97 |
| Engine Hours | 875 | 875 | 875 | 875 | 875 |
| Feed rate | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |

The analysis results, based on the tests performed, indicate a significant increase in Fe content across all units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load, the wear is predominantly of the corrosive type. The reserve BN across all units is likely to reflect the running in of the Alucoat piston rings.
Table 5 Sweep Test Results FR 0.63 g/kWh, Castrol Caremax Cylinder Oil Monitor

| CYLINDER UNIT | 1 | 2 | 3 | 4 | 5 |
|----------------|---|---|---|---|---|
| PISTON HOURS SINCE OVH | Hrs | 660 | 660 | 660 | 660 |
| CYLINDER OIL FEED RATE | g/kWh | 0.63 | 1.22 | 0.63 | 0.63 | 0.63 |
| CYLINDER OIL | CYLTECH 100 |

| CYLTECH 100 |
| Base Number | 9.8 |
| Base Number | 12.5 |
| Total Water | 5vol | 0.54 |
| Total Water | ppm | 0.49 |
| Iron (Fe) | ppm | 431 |
| Iron (Fe) | ppm | 709 |
| NPA | ppm | 119 |
| Lead (Pb) | ppm | 3 |
| Copper (Cu) | ppm | 32 |
| Aluminum (Al) | ppm | 25 |
| Chrome (Cr) | ppm | 15 |
| Molybdenum (Mo) | ppm | 23 |
| Silicon (Si) | ppm | 51 |
| Nickel (Ni) | ppm | 225 |
| Vanadium (V) | ppm | 761 |

| % S in Fuel | 79 |
| Load (kW) | 2.97 |
| Engine Hours | |
| Feed rate | 0.97 |

| DURING SAMPLING % MCR | 18.11.18 | 18.11.18 | 18.11.18 | 18.11.18 | 18.11.18 |
| Date Sample Taken | |
| Base Number | mgKOH/g | 9.8 | 11.9 | 12.7 | 18.4 |
| Base Number | mgKOH/g | 12.5 | 15.4 | 16.5 | 24.6 |
| Total Water | 5vol | 0.54 | 0.49 | 0.44 | 0.66 |
| Iron (Fe) | ppm | 431 | 566 | 653 | 538 |
| Iron (Fe) | ppm | 709 | 818 | 996 | 661 |
| NPA | ppm | 119 | 180 | 194 |
| Lead (Pb) | ppm | 3 | 1 | 2 | 4 |
| Copper (Cu) | ppm | 32 | 39 | 61 | 40 |
| Aluminum (Al) | ppm | 25 | 22 | 30 | 29 |
| Chrome (Cr) | ppm | 15 | 15 | 21 | 18 |
| Molybdenum (Mo) | ppm | 23 | 22 | 28 | 25 |
| Silicon (Si) | ppm | 51 | 48 | 59 | 66 |
| Nickel (Ni) | ppm | 225 | 190 | 252 | 255 |
| Vanadium (V) | ppm | 761 | 638 | 842 | 875 |

The analysis results, based on the test performed, indicate a significant increase of Fe content across all units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load, the wear is predominantly of the corrosive type. The reserve BN across all units is approaching the below safe margin.

Analysis of the sweep test results indicate feed rates of 1.38 g/kWh and 1.22 g/kWh as close to optimal for HFO with Sulphur content of 2.97. Any further reduction will increase risk of corrosive wear.

However, legislative changes forced operators to use low Sulphur fuel only. This negates possibility of the corrosive wear, however, it does significantly increase risk of bore polishing. With low/no Sulphur fuels, the only way to ensure correct dosing is to change BN value through mixing unit.

Note that in dual fuel installation, fuel changeover will occur in two scenarios:
- Change from liquid fuel to gas, done at certain, predefined loads
- Change from gas to liquid fuel – achieved with preparation of the engine for low load operation, due to SECA requirement or due to operational problems.

Source: (Castrol, 2020)
Therefore, it is of most importance to carry out frequent scavenge spaces inspections – this is in order to ensure polishing does not occur.

![Fig. 14 Recommended BN levels for MAN B&W Engines](source: MAN Diesel & Turbo, 2019)

Based on experience gathered to date, BN value for gas operation is set at 40. This requires frequent inspections to be carried out as well as periodical operation on high BN oil (Cyltech 100).

![Fig. 15 Deposit control](source: MAN Diesel & Turbo, 2019)
Figure 16 displays cylinder unit in excellent condition, operating in gas mode for over 10K running hours. Deposits on first ring land indicate a need for period of high BN operation. Trialled procedure calls for three days run with CLO 100 BN.

Fig. 16 Feed rate of 0.6 g/kWh with CLO BN 40
Source: Author’s own Nov 2018

Figure 17 presents same unit, after high BN run. It is evident ring lands were cleaned out of all deposits.

Fig. 17 Feed rate of 0.6 g/kWh after 72 hours operation with CLO BN 100
Source: Author’s own Nov 2018
CONCLUSION
Introduction of MARPOL Annex VI – Fuel Sulphur Limits, forced owners and operators to use various BN cylinder oils. It is therefore not possible to operate the engines within expected wear margins without continuous change to its operational parameters. To be able to adjust/change these parameters, marine engineer must understand the whole process of liner lubrication, which requires adjustment based on empirical data being gathered continuously through the vessel’s life. Nothing will replace frequent scavenge spaces inspections as well as very close monitoring of feedrate and Base Number of the cylinder oil.

REFERENCES
Antturi, J. et al. (2016) ‘Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping’, Journal of Environmental Management, 184, pp. 431-440. doi: 10.1016/j.jenvman.2016.09.064.
Castrol (2020) Castrol Caremax Cylinder Oil Monitor. Available at: https://www.castrol.com/en_gb/united-kingdom/home/marine/services/caremax-machinery-health-monitor.html (Accessed: 15 February 2020).
Chu Van, T. et al. (2019) ‘Global impacts of recent IMO regulations on marine fuel oil refining processes and ship emissions’, Transportation Research Part D: Transport and Environment, 70, pp. 123-134. doi: 10.1016/j.trd.2019.04.001.
Chybowski, L. et al. (2016) ‘An engine room simulator as an educational tool for marine engineers relating to explosion and fire prevention of marine diesel engines’, Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie, 43(115), pp. 15-21. doi: 10.17402/034.
Chybowski, L., Laskowski, R. and Gawdzińska, K. (2015) ‘An overview of systems supplying water into the combustion chamber of diesel engines to decrease the amount of nitrogen oxides in exhaust gas’, Journal of Marine Science and Technology, 20(3), pp. 393-405. doi: 10.1007/s00773-015-0303-8.
Gawdzińska, K. et al. (2018) ‘The impact of reinforcement material on selected mechanical properties of reinforced polyester composites’, Composites Theory and Practice, 18(2), pp. 65-70.
Gawdzińska, K. et al. (2019) ‘A Study of Metal-Ceramic Composite Foams Combustibility’, Acta Physica Polonica A, 135(2), pp. 304-307. doi: 10.12693/APhysPolA.135.304.
Gawdzińska, K., Chybowski, L. and Przetakiewicz, W. (2017) ‘Study of Thermal Properties of Cast Metal-Ceramic Composite Foams’, Archives of Foundry Engineering, 17(4), pp. 47-50.
Laskowski, R., Chybowski, L. and Gawdzińska, K. (2015) An engine room simulator as a tool for environmental education of marine engineers, Advances in Intelligent Systems and Computing. doi: 10.1007/978-3-319-16528-8_29.
MAN B&W Diesel A/S (2013) MAN B&W 50-90 MC/MCE Instruction Manual. Copenhagen.
MAN Diesel & Turbo (2015) Service Experience 2014. Copenhagen.
MAN Diesel & Turbo (2018) Operation on Low-Sulphur Fuels. MAN B&W Two-stroke Engines. Copenhagen.
MAN Diesel & Turbo (2019) Service Letter MAN B&W SL2019 – 671. Copenhagen.
Nozdrzykowski, K. (2006) ‘Error Analysis of Graphical Interpretation of Circularity Profile’, Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie, 10(82), pp. 329-338.
Nozdrzykowski, K. (2018) ‘Applying Harmonic Analysis in the Measurements of Geometrical Deviations of the Crankshafts – Selecting Support Conditions’, MAPE, 1(1), pp. 191-195. doi: 10.2478/mape-2018-0025.
Nozdrzykowski, K. and Bejger, A. (2013) 'Aspects of using correlation calculus in comparative measurements of geometric deviations and shape profiles of main crankshaft bearing journals', Zeszyty Naukowe Akademii Morskiej w Szczecinie, Scientific Journals of the Maritime University of Szczecin 2, 35(107), pp. 114-117.

Nozdrzykowski, K. and Chybowski, L. (2019) 'A Force-Sensor-Based Method to Eliminate Deformation of Large Crankshafts during Measurements of Their Geometric Condition', Sensors, 19(16), p. 3507. doi: 10.3390/s19163507.

Nozdrzykowski, K., Grządziel, Z. and Harušinec, J. (2018) 'Determining and Analysing Support Conditions at Variable Construction of Crankshafts', New Trends in Production Engineering, 1(1), pp. 553-560. doi: 10.2478/ntpe-2018-0069.

Nozdrzykowski, K. and Janecki, D. (2014) 'Comparative studies of reference measurements of cylindrical surface roundness profiles of large machine components', Metrology and Measurement System, XXI(1), pp. 67-76.

Wang, Z., Zhang, H. and Gan, X. (2019) 'Research on Solution of Ship Low Sulphur Fuel based on IMO Sulphur Limitation Regulation', IOP Conference Series: Earth and Environmental Science, 401, p. 012012. doi: 10.1088/1755-1315/401/1/012012.

Abstract: The deformation of a part occurring in the process of grinding directly influences its exploitation and quality parameters. The instability of shape and size, which occurs due to an imbalance of residual stress, can be the one of the major causes of deformation of a part. The decrease in stress slows down the deformation process. Considering the regularities of heat source intensity dependence on the grinding modes, it can be asserted that with increasing grinding depth and grinding wheel hardness, the value increases and it decreases with a growth in a speed of the part and the use of cooling. The higher the heat removal is and the better lubricant properties of the liquid are, the more significant the decrease in is. Changing these values allows regulation of the residual stresses. As a result of the research on determination of deformations, it is recommended to reduce thermal deformations by considering the geometric size of a plate to be machined, linear expansion coefficient of plate material and an allowance for nonflatness from thermal deformations. The value of nonflatness from thermal deformations is directly proportional to linear expansion coefficient of plate material and its square overall dimensions. At the same time, the value of nonflatness is inversely proportional to the plate thickness.

Keywords: deformation, stress state is determined, stress diagram, scheme of residual stress formation, grinding