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Application of X-S Control Cards to Parameter Control in the Machining Process of Piston Castings for Internal Combustion Engines

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Abstract

This article discusses the possibility of using a two-track X-S control card on a Mesas device to control the production process parameters of piston castings for combustion engines. The research was carried out at the Federal-Mogul Gorzyce company. The basis for estimating the variability of the process results from the mean value (X) is the standard deviation (S). Thanks to specially designed measuring stations that use algorithms to calculate process indicators (C_p and/or C_{pk}) and their visualization, the cost of manufacturing products and the number of non-compliant products (scraps) are reduced. The process stability was investigated by measuring the key dimensions of the piston casting in a specific population and a given measurement cycle. Taking into account the precision of details, their technical condition, and surface quality, the production machines and cutting tools were optimally selected. It has been found that an important element of the effective use of Statistical Process Control (SPC) are trained/experienced operators who can correctly interpret the resulting control chart forms.

Keywords: Control cards, Casting quality management, SPC, Pistons for internal combustion engines

1. Introduction

Control cards, even though they have been known for years, are one of the most important tools for controlling and detecting process instability. Their popularity is due to the simple design and advantages, which include [1÷4]:

- high efficiency in preventing defects during the process,
- avoidance of unnecessary machine and process adjustments,
- providing diagnostic information about process stability,
- the possibility of determining the process capability indexes, indicating its qualitative efficiency.

The idea of using control cards is to determine when in a process, e.g. in production, there is an atypical sample whose characteristic feature, e.g. size or shape, is different from the others. This can be determined using statistical tests to measure the position and dispersion of results, which requires calculations [5÷7] or by using control charts, allowing to obtain the same conclusions, but in a graphical way. These methods come down to the "tracking" of measurements, the results of which exceeded the control lines [8]. Depending on the specific features of the product using the control card, the following can be measured:

- one variable - the so-called "Single-track card" containing a single chart or
- two variables - the so-called a 'two-track card' with two graphs or
- several variables - the so-called "multi-track card" containing several graphs.

2. Research Problem

Pistons for internal combustion engines are produced using many processes and manufacturing operations. The key areas of a piston manufacturing plant are:

- melting plant where the required alloy is prepared,
- foundry where gravity casting moulding takes place,
- heat treatment (mainly the ageing process),
- machining with inter-operational inspection, which includes, among others: riser milling, rough turning, valve pocket milling, oil hole drilling, piston pin hole rough boring, piston skirt fine turning and non-destructive testing (ultrasound, eddy currents),
- chemical treatment (phosphating, surface activation, anodizing of grooves for piston rings), graphitizing of a part of the piston skirt surface, graphite annealing,
- final quality control, which covers 100% of the pistons (incl. the final dimensional inspection),
- assembly of components, marking and visual inspection,
- packing and shipping products to the customer.

Based on the statistical data collected from the final quality control, it was found that many non-conforming pistons are manufactured during the machining stage (approximately 40% of all defects). Considering that Federal-Mogul produces approximately 1 million pistons per year in one production line, this is approximately 40,000 scraps. These non-conformities are detected only at the end of the production process during the final inspection, which generates additional losses.

As shown in the inspection plan, the main disadvantage of the dimensional deviation turned out to be the diameter of the piston skirt (3% scraps coming out of skirt turning). This parameter is critical in terms of ensuring the functionality of the piston and the correct operation of the piston-ring-cylinder system. Detection of defective products at the moment of their creation allows reducing production costs (materials, labour consumption, energy and other utilities) in further processing. If therefore, the non-conformities can be eliminated at their place of origin, such pistons would not be further processed, which will reduce the aforementioned costs. In addition, the load on machines and material consumption in the subsequent stages of piston production will be reduced.

Therefore, the key is to control the dimensional inconsistencies at the place of occurrence, i.e. the settings of CNC machines and to determine the lifetime of the cutting tools. The purpose of this control is to implement actions in the place of process instability and to obtain feedback on the quality of machining parameters. It should be emphasized that there are product buffers between the CNC machines and the final quality control, which significantly affects the waiting time for feedback on the adjustment of the parameters of CNC machine tools.

According to the data from Federal-Mogul Gorzyce, the losses resulting from such a process are too high, hence the decision to implement corrective and preventive actions.

Taking into account the specificity of the production of pistons in plants supplying products for the automotive industry, it was decided to pilot the implementation of inter-operational statistical process control (SPC) for the critical dimension (piston skirt diameter) using a double control chart XS (X - expected value, S - deviation standard) in the production of engine pistons using the MESAS SPC machine/computer.

3. Purpose and Scope of Research

The aim of the research was to reduce the number of defective products and thus to lower production costs (labour consumption, materials, energy) through ongoing monitoring of the machining of pistons for internal combustion engines, using the X-S double-track control card. To evaluate the correct course of the process, the measurement of the diameter (DN) of the piston skirt (a critical dimensional parameter) for a gasoline engine (1400 cm3 - the largest share of orders) at a height of 12.4 mm was selected. It is the largest diameter at the height of the piston skirt. The research was carried out in Federal-Mogul Gorzyce on a selected machining line on which a specially designed MESAS SPC device was installed.

The scope of the research includes:

- measurement of the diameter of the piston skirt for k = 25 subgroups with the number of samples in the subgroup n = 3 (75 pistons),
- making calculations and X-S measurement histograms,
- making calculations and measuring histograms X-S,
- summary and conclusions

4. Control Stand and Research Methodology

The stability of the machining process was assessed by measuring the diameter of the piston skirt from a batch of 75 castings (Fig. 1). According to the SPC method [9], 3 pieces were randomly collected every hour from 189 pistons produced within 1 hour, with a minimum number of subgroups of 25 pistons.

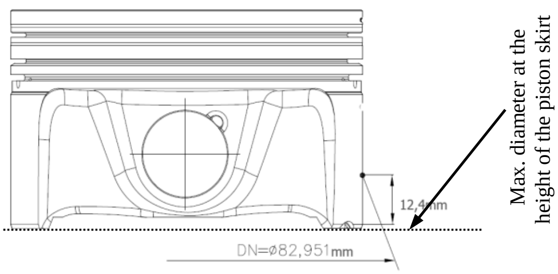


Fig. 1. Side view of the engine piston

The diameter of the piston skirt was measured on the MESAS SPC test station shown in Figure 2.

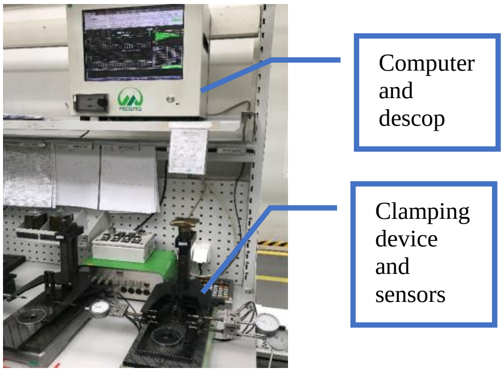
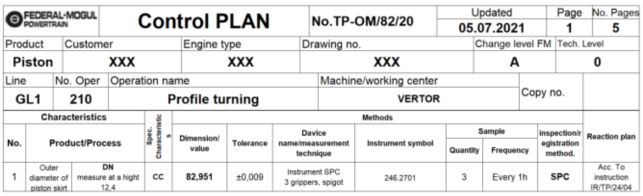


Fig. 2. View of the station for measuring the diameter of the engine piston skirt under test (materials from Federal-Mogul)

The measuring station consists of a mounting device, a device fixing the position of the piston, dial gauges (accuracy 0.001 mm) connected with a computer and a control panel. The inspection process is operated by an operator who measures three pistons every hour according to the product control plan during the entire production shift (8 hours).

The scope of dimensional control includes the measurement of the diameter DN of the piston skirt at the point specified in Figure 1. A fragment of the piston inspection plan is shown in Figure 3.



FEDERAL-MOGUL POWERTRAIN	Control PLAN	No.TP-OM/82/20	Updated	Page	No. Pages
			05.07.2021	1	5

Product	Customer	Engine type	Drawing no.	Change level FM	Tech. Level
Piston	XXX	XXX	XXX	A	0

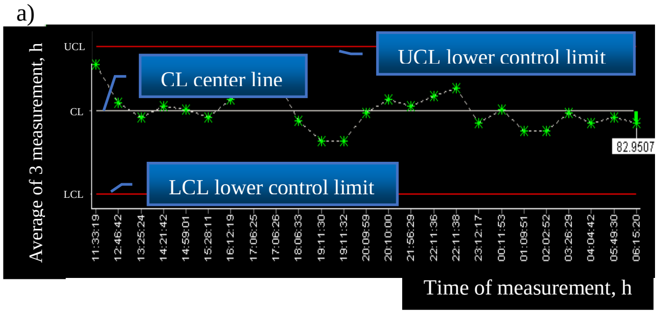
Line	No. Oper	Operation name	Machine/working center	Copy no.	
GL1	210	Profile turning	VERTOR		

Characteristics			Spec. Characteristics	Methods							Reaction plan
No.	Product/Process			Dimension/ value	Tolerance	Davice name/measurement technique	Instrument symbol	Sample		inspection/registration method.	
								Quantity	Frequency		
1	Outer diameter of piston skirt	DN measure at a hight 12,4	CC	82,951	±0,009	Instrument SPC 3 grippers, spigot	246.2701	3	Every 1h	SPC	Acc. To instruction IR/TP/24/04

Fig. 3. Fragment of the control plan

Statistical control of the production process is supported by X-S cards, which show possible disruptions in the process. The graph shows the parameters that are crucial for the evaluation of the quality of the process, variable in time, e.g. the average of the mean measurement results and the standard deviation. Measurement results and other parameters are plotted on two charts (two tracks) with control lines: top, bottom and centerline (Fig. 4).

a)



b)

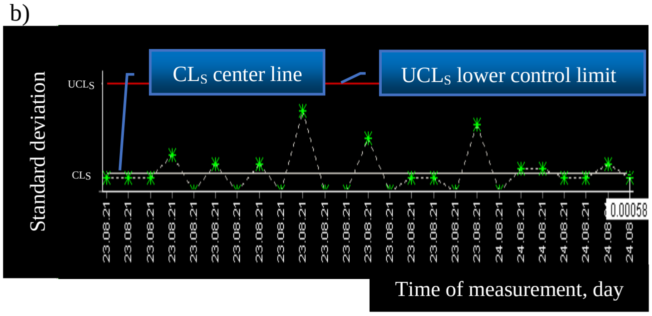


Fig. 4. X-S card: a) first chart (X); b) second chart (S)

The following formulas (for the first chart) were used to calculate the centre line and control lines - Figure 4a:

- center line CL:

$$\bar{\bar{x}} = \frac{\sum \bar{x}}{k} \quad (1)$$

- upper control limit UCL:

$$\bar{\bar{x}} + A_3 \cdot \bar{S} \quad (2)$$

- lower control limit LCL:

$$\bar{\bar{x}} - A_3 \cdot \bar{S} \quad (3)$$

(for the second chart - S) - figure 4b:

- center line CL_S:

$$\bar{S} = \frac{\sum S}{k} \quad (4)$$

- upper control limit UCL_S:

$$B_4 \cdot \bar{S} \quad (5)$$

- lower control limit LCL_S:

$$B_3 \cdot \bar{S} \quad (6)$$

where:
k = number of subgroups, k=25,
n = number of samples in a subgroup, n=3,
$\bar{x}$ = the average value of subgroup,
$\bar{\bar{x}}$ = grand average,
A_3, B_3, B_4 – multipliers tabled in PN-ISO 8258+AC1 standard,
S – standard deviation,
$\bar{S}$ - average standard deviation.

5. Results of Research

The signals from the sensors are automatically imported into the MESAS program, which generates appropriate graphs, measurement results and calculations, e.g. the C_p and C_{pk} index. A model view of the control card dialogue with the designations of the machining process of piston castings is shown in Figure 5.

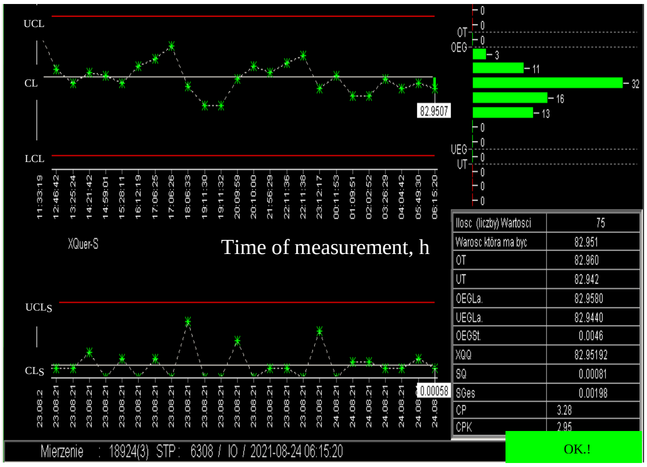


Fig.5. The MESAS program dialogue for measuring the skirt diameter of the piston (Federal-Mogul Gorzyce materials)

After the measurements, the MESAS program calculates the qualitative capacity of the machining process of engine pistons determined by the C_p and C_{pk} indexes, which were calculated from the following dependencies [10].

$$C_p = \frac{T}{6S} \tag{7}$$

$$C_{pk} = \frac{T_g - \bar{\bar{x}}}{3S} \tag{8}$$

$$C_{pk} = \frac{\bar{\bar{x}} - T_d}{3S} \tag{9}$$

where:
T – the width of the tolerance,
T_g – upper tolerance limit,
T_d – lower tolerance limit.

In the case of C_{pk}, the lower score is selected for evaluation [10].

The C_p and C_{pk} indicate the influence of special causes of process variability and guarantee the quality of finished products (piston) required by customers.

The C_p index determines how many times the spread is within the tolerance field. The bigger the index, the better. In the automotive industry, C_p is expected to be a minimum of 1.33 [11].

C_{pk} specifies the centring of the process. The minimum value of the indicator is also 1.33.

The results of the measurements of the diameter of the piston skirt DN are presented in Table 1.

Table 1.
Data and measurement results

Parameter, unit	**Result**
Number of measurements, pieces	75 (25x3)
DN, mm	82,951
T_g, mm	82,960
T_d, mm	82,942
UCL, mm	82,958
LCL, mm	82,944
UCL_S, mm	0,0046
CL, mm	82,95192
CL_S, mm	0,00081
C_p	3,28 required min. 1,33*
C_{pk}	2,95 required min. 1,33*

* - according to [11], the Cp and Cpk indicators, in the automotive industry are at least 1,33.

When analyzing the results in Figure 4a (chart 1), characteristic trends can be noticed. They are marked in Figure 6. The method of arranging subsequent points and the analysis of the standard [9] indicate that this trend is typical for the machining process, and the process is stabilized and depends on the production technology implemented in the machining line.

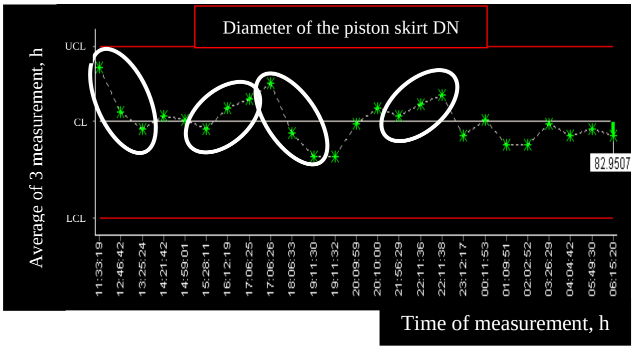


Fig. 6. Chart 1 with characteristic trends marked (materials from Federal-Mogul)

6. Summary

The purpose of the control cards is to inform about the deviation of the process from the target (normative) value, which may be, for example, a nominal dimension or, for example, an acceptable deviation. The effective use of statistical process control (SPC) allows its user to significantly reduce the number of defective products, and thus reducing production costs and reducing the risk of complaints. The key is the correct implementation of the SPC control process, i.e. selecting the measurement site, identifying the variables, the number of samples and understanding the results of the indicators. Employee discipline is also important, consisting in taking correct measurements, collecting the appropriate number of products for inspection at a given time and place.

For the pilot assessment of the correctness of the course of machining, a two-track X-S control chart was used to measure the diameter of the shell of 25 subgroups of pistons, each consisting of 3 pieces, according to the SPC recommendations [9 ÷ 11]. Thus, 75 randomly selected items from 189 pistons produced per hour were tested. The research was carried out with the use of the MESAS SPC device. Using the dependencies from 1 to 6, the characteristic lines on the X-S cards (Figs. 5 and 6) and the process indicators C_p and C_{pk} (formulas 7-9) were determined.

As the research shows, the X-S double-track control with preset normative values can be used to monitor the correctness of the course of the machining process of castings, without preliminary tests. However, it is recommended that a preliminary sample be taken as the values of the control lines are calculated from the design data. The use of such a method, in addition to information about the dysregulation of the process (or its stabilization), informs whether the results of the process differ from the normative value.

The presented data show that on the X-S control chart (Fig. 6) there are successively repeated points with values that increase or decrease. This perfectly reflects the technological process of machining, in which one of the key elements is the life of the cutting tools. As they wear out, the trend line tends to rise up until the machine operator corrects the machining program settings and (or if necessary) replaces the tool with a new one. This image is consistent with what is described in the PN-ISO 8258 + AC1 standard and can be interpreted as consistent with the expectations when designing the process and with its control under production conditions.

The results in Table 1 also show that the process is well supervised and controlled, and the corrections resulting, for example, from the wear of cutting tools, are properly introduced. This is also evidenced by the C_p and C_{pk} indicators [10, 11], the values of which exceed the minimum requirements and represent the production process with low dispersion and good centering for DN diameter. The probability of the occurrence of 3 consecutive points with constantly increasing or decreasing values can be estimated assuming that the number of their different combinations is 3! And only one arrangement corresponds to the trend (increasing or decreasing). Thus, this probability is:

$$\frac{1}{3!} = \frac{1}{6} \approx 0.166(6) \approx 16.6\% \qquad (10)$$

and for machining processes it is balanced.

A well-designed technological process and its control plan guarantee, for the critical characteristics of the product, reproducible results that do not exceed the tolerance limits. The key in this area is the training and awareness of the employees performing the measurements and the ability to interpret the results on the X-S card. It is important to react immediately and appropriately in the event of the occurrence of points near the lower or upper limit line and observation of low values of C_p and C_{pk} indicators.

The presented research shows that the use of the X-S double-track control cards and the maintenance of SPC for critical characteristics can completely eliminate products inconsistent with the measured parameters and potentially reduce the number of complaints from customers.

After training the personnel in the correct interpretation of the control cards, the management of Federal-Mogul Gorzyce decided to apply them to the remaining lines for the mechanical processing of pistons for internal combustion engines.

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