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CASE STUDY

Application of TPM indicators for analyzing work time of machines used in the pressure die casting

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Abstract The article presents the application of total productive maintenance (TPM) to analyze the working time indicators of casting machines with particular emphasis on failures and unplanned downtime to reduce the proportion of emergency operation for preventive maintenance and diagnostics. The article presents that the influence of individual factors of complex machinery maintenance (TPM) is different and depends on the machines' modernity level. In an original way, by using correlation graphs, research findings on the impact of individual TPM factors on the castings quality were presented and interpreted. The examination results conducted for machines with varying modernity degrees allowed to determine changes within the impact of individual TPM factors depending on machine parameters. These results provide a rich source of information for the improvement processes on casting quality of the foundry industry that satisfies the automotive industry demand.

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Introduction

The TPM allows the smooth functioning of machinery and equipment, which nowadays is a condition that the company must meet to be a competitor in providing high-quality products in the shortest possible time. It should be noted that the customer is increasingly aware and demanding. To meet the growing customer demand, enterprises are required to improve production systems at each stage of the product manufacturing, from design through the manufacturing process until its finishing (Zahra Shad et al. 2014).

Pressure die casting is the most efficient and accurate method for forming a product from the liquid metal in the metal mold, which is fixed on the machine pressure (Fajkiel et al. 2008). Pressure molding differs from the conventional casting methods which are based on slow mold filling (Braszczyński 1989; Perzyk 2000; Górny 2008). Injection molding is characterized by the administration of pressure to the molten metal (Białobrzeski 1992). Molding pressure is applied to the mass production of castings for small and medium-weight, any shape, dimensional accuracies and large thin-walled. Depending on the purpose of the device, a particular type of alloy is used with the specific characteristics of chemical composition and mechanical properties as specified in PN-EN 1706:2001 (Budziaszek et al. 2004; Górny 2008).

Pressure die casting is still growing and is aimed to complete manufacturing process automation. In pressure die casting, the most important characteristics are shaped by casting machines and devices for finishing.

Pressure die casting machines are classified according to (Białobrzeski 1992; Piszak 1986):

- the bale chamber type (in which pressure is applied to the liquid alloy),
- drive type,
- pressure chamber system,
- other structural characteristics.

From a technological point of view, there is distinction between hot- and cold-chamber pressure casting systems (Białobrzeski 1992). The disadvantages of small hot chamber machines are their lack of durability and need of piston rings to be replaced frequently. These machines are maintained at a lower pressure than the cold-chamber machines. In the case of cold-chamber machine there is a machine with a horizontal chamber with due to the shorter path from the chamber liquid alloy into the mold cavity pressure. Another advantage of the machine with cold-chamber pressure is less wear sliding, compared to corresponding machines with vertical-pressure chamber. These machines also have better performance, due to limitations in the activities carried out by hand (Dańko 2000). In modern machines with horizontal cold-chamber pressure, bale chamber system achieved increasing compaction pressure. Horizontal cold-chamber machines are the most popular machines used in pressure casting. Figure 1 shows the basic division of the cold-chamber machines (due to the location of the fill chamber).

In an aim to present the basic activities of pressure machine, regardless of the machine type, the following major components are listed (Dańko 2000; Waszkiewicz 1995; Czajkowska et al. 2008; Jostes and Helms 1994):

- hydraulic power unit which is the source of energy used to drive hydraulic motors, hydraulic valves and hydraulic servo control. It includes one or more electric pumps, tanks and fuel filter medium (oil) and a system of valves,
- jumper-locking, whose task is to short-circuit and open a form and keep it in a compacted state jumper at a maximum pressure during filling and solidification of the melt.

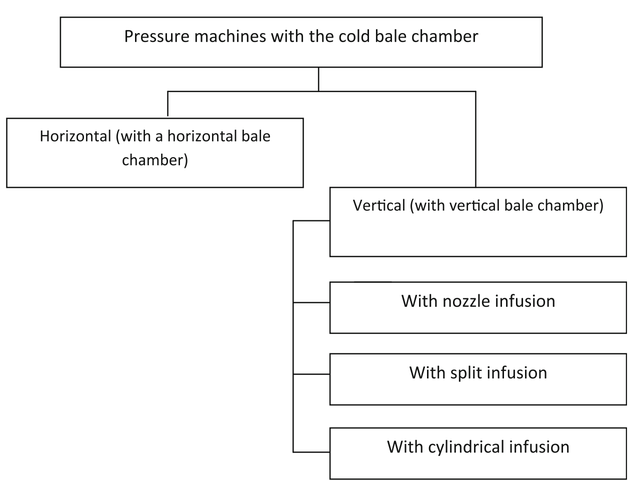

Fig. 1 Distribution of cold-chamber machines within the fill chamber location. Source: own study based on (Dańko 2000; Mielczarek and Borkowski 2008)

An important function is to increase the presser unit (multiplication) to a desired value and maintain the level of pressure applied to the alloy during solidification and subsequent removal of the excess of the disc presser cylinder solidified alloy. The ironing system is a system of determining the filling of the mold cavity pressure. It is the most important team of construction machinery, used to perform tasks established technology. The ironing system has undergone many structural changes from single phase to three- or four-stage cycle piston.

Pressure equipment design solutions produced by specialized companies are very diverse, mainly due to non-infringement of other claims and often due to the different concepts of the construction machinery. Modern machines are characterized by high-pressure operational reliability, lower energy consumption and less harmful impact on the environment compared with previous solutions (Perzyk 2000; Bonderek and Chromik 2006). Automation of foundry processes and above all modern machines have reduced the occurrence of some of the discrepancies. There is a share of human errors in the incidence of non-compliance. In the case of automatically operated machinery, for example, there is no inconsistency arising from the very small portion of the alloy infused into the chamber (which resulted from the manual dosing). Automation of casting machines, unfortunately, does not completely eliminate human error, but merely its effects (Bonderek and Chromik 2006; Mielczarek et al. 2008). Despite the formation of a continuous casting process automation, where computer programs on the basis of previous experience, numerical simulation and statistical tests determine the amount of temperature distribution vents, etc., we still have to deal with a large number of non-conformations. Despite high automation of foundry processes ranging from programs used to design forms with automatic priming process, there is continuation of research related to (Baliński 2003): the casting process efficiency increase, dimensional inspection, improvement of casting alloys and their properties, use of form filling process simulation, residual stress and the processes occurring in the forms of pressure, layers separating and environmental protection management.

Increasing attention has been paid to the analysis of machine time to reduce the proportion of emergency operation for preventive maintenance and diagnostics (Elliot and Hill 1999; Bamber et al. 1999; Ireland and Dale 2001;

http://www.przeglad-techniczny.pl/arch/2006/12/daleka_droga.htm; Elahe Faghihinia 2012). In times of pressure die casting, machine operation analysis leads to higher productivity casting process, improves casting quality and reduces waste. Increasingly, the casting position is not determined by the tonnage, but by the type and quality of castings (http://www.przeglad-techniczny.pl/arch/2006/12/daleka_droga.htm). In a highly competitive market, the quality of die castings for the automotive industry is very important. It is a guarantee of the durability of parts and components of the final product (Fajkiel et al. 2008; http://www.przeglad-techniczny.pl/arch/2006/12/daleka_droga.htm).

Operation of machinery and equipment deals with the analysis of technical objects working in production, both during their use, as well as during use (maintenance, repair). However, reliability is associated with the ability to save the state machine fitness at a given time and under certain operating conditions (Mielczarek and Borkowski 2008).

With accordance to PN-93/N-50191 document, reliability is a set of characteristics that describe the readiness of the facility and affecting it: reliability, service and provide proof functionality of service. Reliability is a relative concept, because there are different requirements for an object, and the reliability of these same objects can be based on several factors (depending on the requirements in different operating conditions) (Elliot and Hill 1999; Fajkiel et al. 2008). From the theory standpoint of the operation of machinery and equipment, each technical unit within the company requires manual service. It has a specific purpose of use, has a determined destiny and determined permanence, surrenders to damage and can be improved, but first of all it should not pose a threat to man. Optimal operating conditions are determined according to the elemental life of the equipment, which consists of the device tested, the crew of the device, subject to the operating device, the position of use and handling equipment, environment and power supplies equipment, supplies and equipment performance information (Elliot and Hill 1999).

Proper operation of machinery and equipment depends on appropriate security and ensuring their work continuity and efforts to improve their performance. To implement this assumption, the producers should adhere to certain operating conditions, as well as fixed-cycle planned preventive maintenance (Borkowski and Selejdak 2007). Approved maintenance programs and ongoing improvements to the maintenance of machinery ensure the high quality of products, improve production rhythm, improve economic indicators due to production cost reduction, utilization of full capacity of machinery and equipment, reduce or eliminate failures, reduce repair costs, extend the durability of machinery and equipment, economically use electricity by reducing power consumption and maintain high culture jobs (Borkowski and Selejdak 2007; Jostes and Helms 1994; Charles-Owaba et al. 2008; Ghayebloo and Babaei 2010).

Table 1 Advantages of applying the TPM system

Element of assessment	TPM
Costs	Productivity improvement by reducing the maintenance costs of machinery and equipment
	The lower level of inventories
Machine	Activities aimed at the prevention of accidents, extending the life of machinery
Product	Reducing the number of deficiencies
	Ensuring higher quality at every stage of the technological process
Worker	Qualifications increase
	Work comfort level increase
	Work safety increase

Source: own study based on (Borkowski and Selejdak 2007)

There are four maintenance strategies (html and February 2014):

- reactive maintenance, which allows the machine to run until failure,
- periodic preventive maintenance,
- preventive maintenance based on inspections,
- maintenance based on remote monitoring of parameters describing the condition of the device.

The best solution is to keep a remote monitoring based on the parameters describing the technical condition of the device. It should be noted that there is important systematic and continuous improvement of the maintenance system. Table 1 shows the changes in individual enterprise factors as a result of the introduction of the TPM system compared to the traditional approach.

Implementation of the TPM system involves the introduction of an action series aimed at:

- hardware identification and analysis of current performance and efficiency,
- determination of preventive measures and the selection of appropriate tools and measures,
- determining maintenance plans together with an indication of those responsible,
- creating a maintenance manual for each machine,
- training of staff,
- determination of the durations of each activity.

Violation of the rules determining the correct operation of machinery and equipment is associated with careless operation, failure to set working conditions documentation, improper tools, machining parameters, etc. Improper maintenance of machines may lead to unacceptable distortion of machine parts. Deformation of machine parts might have a shape change or permanent deformation of the surface. Surface condition of the machines also contributes to machinery failure. Interacting surfaces are characterized by inequalities, which change during the use of machinery and equipment. As a result of cooperation between the two machine elements, each is associated with a second surface of further deformation.

Experimental

The modernity of the machine parts can be classified with the ABC technology analysis to assess its value and usefulness to the company in the period under consideration (Bamber et al. 1999; Borkowski and Selejdak 2007).

As a measure, the competitive advantage can be used, in terms of the cost leadership or the product wealth. The second one is achieved through flexibility arrangements which will enable the company to produce frequent changes in the type and quality of the product. ABC analysis was invented by Vilfredo Pareto. The purpose of this method is the classification of products and materials into three groups A, B or C, depending on their contribution to product formation. In this paper, this method was used to classify parts of the pressure casting machines according to their impact on shaping the pressure casting product.

The ABC technology analysis is applied in the production of individual components used in the machine and assesses their modernity on Parker's five-point scale. The Parker scale consists of the following levels as shown in Table 2 (Czajkowska et al. 2008; Borkowski and Selejdak 2007).

One use of this categorization is the ability to rank the desirability of modernity in terms of development and investment, which is to decide which of the parts should be upgraded or replaced. Technologies are not isolated from each other; they often form constellations, based on scientific principle teams. Always, however, the ABC analysis technology allows for the selection of relevant technological capabilities for the company and forms part of the core component of category A, fundamental to the company. They are also referred to as part of implementing propulsion technologies as they help to give the product a special attributes, such as a greater degree of smoothness of the surface, which gives the product a competitive advantage in the application or in the favorable prices.

Table 2 Parker scale

Level	Definition	Example
Level 1	Straight parts, it is possible to produce them by means of techniques	Craft machine foundation
level 2	Parts which were manufactured by the technology not changed and known for many years	The standard engine cooling system
level 3	Parts produced using technology dominated, requiring technical expertise	Standard electric motor
level 4	Parts produced with the use of modern technology	Displaying diagnostic market on the computer control panel
level 5	Part being the result of joint application of modern technologies, patented and present only in machine of the specific company	Injection system

Source: own study based on (Borkowski and Selejdak 2007)

Results and discussions

The ABC technology method is applied to evaluate the casting machines' modernity level

The paper presents an effectiveness analysis for two cold-chamber horizontal casting machines:

- IDRA-type semi-automatic machines with clamping force of 700 tons made in 2007 (M1),
- Buhler machine with clamping forces of 660 made in the 1970s (M2).

The modernity level of both machines was determined by using ABC technology. ABC technology analysis is based on the principle, indicating that each statistical group can be divided into several parts. At one end of the distribution, units are conventionally marked with the letter A, which determine the main part of the results. At the other end of the distribution group, there are parts denoted by the symbol C with a small contribution to the results of its operations. The intermediate parts of the group are marked with the letter B. The components classification for groups A, B or C is associated with the role of the component in the production of full cast, which is associated with the machine work cycle. One use of this categorization is the ability to rank the desirability of modernity in terms of its development and investment, which is to decide as to which of the parts should be upgraded (Borkowski and Selejdak 2007; Jostes and Helms 1994). Table 3 shows the components of casting machines, which were evaluated by the Parker scale. The modernity levels for machine 1 and machine 2 are presented in Table 3 and Fig. 2.

The analyzed components present very different levels of modernity and operation. Machine M1 is a semi-automatic machine that carries out up to 29,000 injections per month (November 2008). The average non-conformities level in the production of castings (2008) on this machine is 2.15 %, Machine M2 is more than 35 years old and carries out an average of 16,500 injections per

Table 3 Components of casting machines under examination

The subassembly	Denotation of the machine part	Components
Basic subassembly	A1	Injection arrangement (cylinder, shaft and piston)
	A2	Arrangement of central stuffing
	A3	Collector
	A4	The cooling system
	A5	The flooding system
	A6	The sprinkler
Support subassembly	B1	The battery system
	B2	Clamping unit
	B3	The core system
	B4	The hydraulic system
	B5	Pump system
	B6	The cooling system
	B7	The lubrication system
	B8	The control panel
	B9	The protections
Side subassembly	C1	Base of the machine
	C2	Basis of the injection system
	C3	The electrical system

Source: own study based on (Mielczarek et al. 2008)

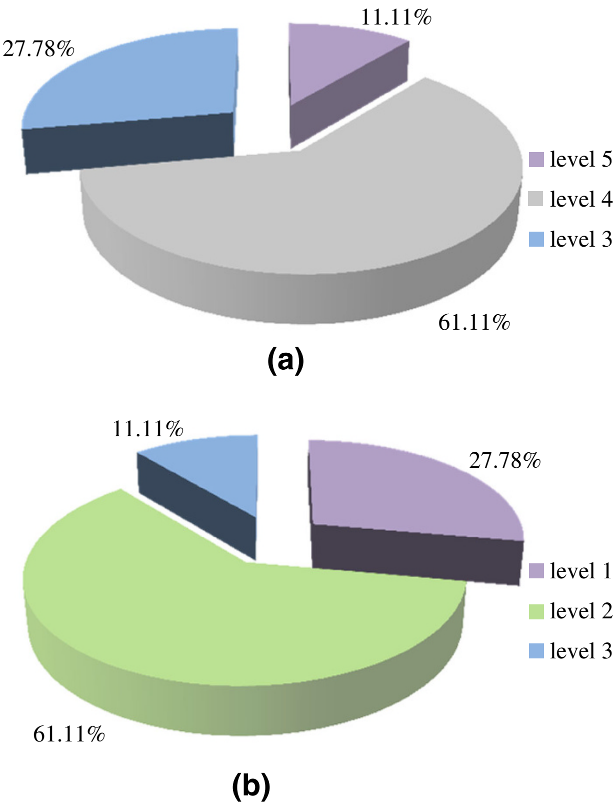

Fig. 2 The structure of the parts' modernity level for: **a** machine No 1, **b** machine No 2. Source: own study

month. The machine generates an average of 3.73 % non-conformities.

In summary, it can be concluded, that the analyzed components of the machine (M1) are at quite a high level of modernity (4). In machine M2, just over 60 % of the parts are on the second level of modernity, 27 % of the evaluated parts are at the first level of modernity and 11 % at the third modernity level. Parts of the basic component in machine M2 were rated at 50 % at the first modernity level. Parts of the machine rated at first modernity level are located in group A3—collector, A5—the flooding system, and A6—the sprinkler. The degree of these parts automation is very important from the standpoint of the casting process automation, degree of disturbance of its operations and consequently the non-conformities level. All parts of the supporting component were estimated at the second levels of modernity, while the C1 machine base and the base of the injection system were evaluated on the first level of modernity. The analysis shows that the machine M2 is located at a low level of modernity. As it is known, appropriately selected and properly applied components contribute to improving the quality of the manufactured products. Not all components are equally affected by the quality of the castings.

In the case of die castings, there are some critical parts such as injection system, cooling system, the automation degree of the flooding method, the mechanism of removing castings from molds and mechanism for applying release agents. In the pressure die casting, the mold automatic temperature control (cooling system) is one of the most important parameters for a full or partial automation of the casting technology, since the correct temperature of the mold and its stability depend heavily on all other process parameters and primarily on the productivity and quality of the castings. Mechanization increases productivity and stabilizes the process, which contributes to castings quality improvement and supports the lower non-conformities levels. The analysis shows that the machine M1 is more automated than machine M2. It is not fully automated, but the modernity level of the majority of the components was highly assessed—the fourth level of modernity.

The dependence analysis between castings machines' operation efficiency and manufactured products

The machines' effectiveness evaluation was carried out with TPM coefficients, which are defined as work machinery and equipment maintenance implemented in the entire enterprise. TPM is broader than the traditional maintenance needed to be involved in the planning and

Table 4 Correlation coefficient r for machines M1 and M2

Machine	Correlation coefficients	TP	TA	WE	WPD	UCD	WW
Machine 1	r	0.710	0.691	−0.711	−0.435	−0.193*	−0.424
	R^2 (%)	50.6	47.7	50.6	18.9	3.7	18.0
Machine 2	r	0.672	0.670	−0.674	−0.674	−0.4761	−0.549
	R^2 (%)	45.2	44.8	45.2	45.5	22.7	30.2

* Statistically insignificant coefficients

Source: own study based on (Mielczarek and Borkowski 2008)

performing of overhaul, repair and legalization of instruments and apparatus, repairing machinery and equipment (Mielczarek and Borkowski 2008).

On the basis of machine working time, taking into account failures and other outages, the analysis for TPM coefficients was calculated: coefficient of operation (WE), coefficient of the speed (WPD), coefficient of utilization (WW) and coefficient of useful operating time (UCD), calculated according to formulas (1), (2), (3), and (4) (Borkowski and Selejdak 2007; Jostes and Helms 1994).

$$\mathrm{WE} = \frac{\mathrm{TZ} - \mathrm{TP}}{\mathrm{TZ}} * 100\,\% \quad (1)$$

$$\mathrm{WW} = \mathrm{WPD} * \mathrm{UCD} * \mathrm{WJ} \quad (2)$$

$$\mathrm{WPD} = \frac{\mathrm{ICJ}}{\mathrm{RCJ}} * 100\,\% \quad (3)$$

$$\mathrm{UCD} = \frac{\mathrm{P} * \mathrm{RCJ}}{\mathrm{TZ} - \mathrm{TP}} \times 100 \quad (4)$$

To determine how (and if) TPM factors and individual failure times affect the quality of castings used in the correlation coefficient r, the correlation coefficient r is calculated from the formula:

$$r = \frac{\mathrm{cov}(x, y)}{\sigma x \ \sigma y} \quad (5)$$

where σχ is the standard deviation of variable x and σγ is the standard deviation of variable y.

The dependences analysis between the non-conformities level (PN) and downtime (TP), breakdown time (TA), coefficient of operation (WE), coefficient of speed (WPD), coefficient of useful operating time (UCD) and coefficient of utilization (WW) are shown in Table 4.

Unplanned downtime is divided into failures mold (TA_f) and other failures of the machine (TA_m). The division of tolerance forms and other equipment failures, not found in the literature, will more precisely identify the main causes responsible for the reduction in the casting quality level.

The impacts of individual factors of TPM: breakdown time (TA), downtime (TP), coefficient of operation (WE), coefficient of utilization (WW), the coefficient of speed (WPD), the useful operating time, time of accident forms

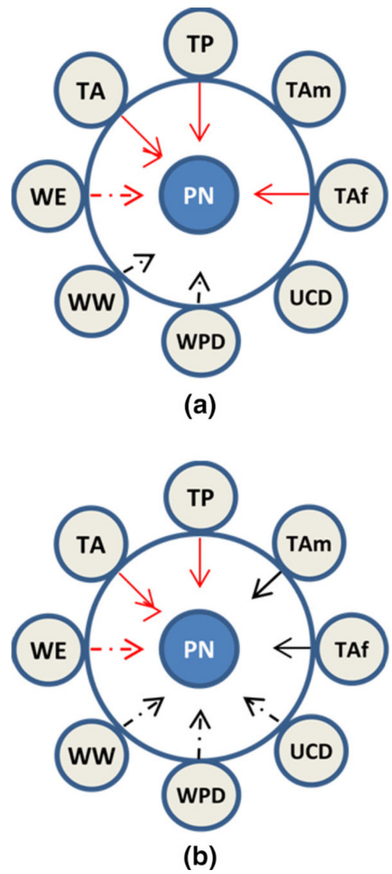

Fig. 3 Correlations graphs between the non-conformity level (*PN*) and variables *TP*, *TA*, *WE*, *WW*, *WPD*, *UCD*, TA_f, TA_m: **a** M1, **b** M2 (Mielczarek and Borkowski 2008)

(TAF) and the time machine failure (TAM) on the level of quality (BS—represented as the level of non-conformity) are presented in the form of the correlation graph (Fig. 3). The circle graph has a radius equal to 1, which means that the maximum value is r. The length of the segment (arrows) from the outer circle to the center inform about the strength of the correlation (Ostasiewicz et al. 2006):

⟶ positive correlation,

–·→ negative correlation.

Absence of an arrow indicates a lack of correlation between variables. In the analysis, the failure time was divided into breakdown of the form failure and machine breakdown due to the high frequency of this failure type.

The analysis of Fig. 3 shows that for both analyzed machines there are:

- significant positive correlations between the downtime (TP), breakdown time (TA), forms breakdown (TAF) and the non-conformity level (PN),
- significant negative correlation between the coefficient of operation (WE), coefficient of speed (DPN), coefficient of utilization (WW) and the level of castings non-conformities (PN).

In the case of machine M2, with regard to lack of automatic priming bucket or a lack of the manipulator hand, the share of the work performed by the operator increases, which means that UCD achieves lower values than the machine M1. As shown in Fig. 3, it determines the occurrence of the non-conforming product (22 %).

The coefficient of determination for the time of TPM (TA and TP) is presented in Fig. 4a and the degree of determination of non-conforming by the coefficients of the TPM is shown in Fig. 4b.

The analysis of Fig. 4 shows that the presence to the greatest extent of non-conforming product is determined by TP, TA and WE (above 45 %).

The analysis of Fig. 4 shows that the useful operating time significantly affects the quality of the machine in case of machine M2. This coefficient reaches a value of −0.4761, which means that with its increase the number of non-conforming product decreases. The coefficient of speed plays a greater role of action in case of machine M2, which explains the 45.5 % incidence of non-conforming than machine M1 ($R^2 = 18.9$ %).

The percentage share of failures and other stoppages in the total downtime number for machine No 1 and machine No 2 are presented in Fig. 5.

The analysis of Fig. 5 shows that, depending on the equipment modernity level, the percentage share of breakdowns changes within the total downtime machine failure. In the case of machine No 1, the machine downtime is 48 % of the work time. In the case of machine No 2, the machines stoppages take up 65 % of the production time. It can be seen that in the case of machines with a higher modernity level (M1), the number of failures in the total downtime is more than 20 %, while in the case of machine No 2 failures occupy about 39 %.

The primary measure of TPM system is OEE—overall equipment effectiveness. OEE is calculated according to the formula:

$$\text{OEE} = \text{availability} \times \text{performance} \times \text{quality}$$

The use of preventive maintenance through a comprehensive system of operating machines and equipment maintenance leads to achieving higher profits and greater range of satisfied customers. Visible effects associated with the implementation of TPM system can be observed for at least a year. As it was already mentioned, the introduction of the TPM system is associated with a number of activities related primarily to the changes in management thinking and the same machine operators. In Fig. 6 changing value of OEE in the analyzed company for both machines was presented over 4 years (2008–2011).

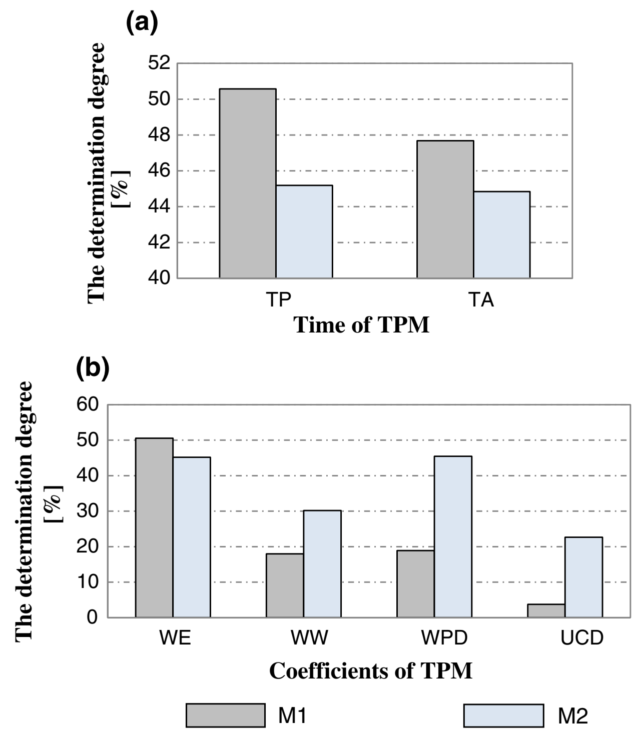

Fig. 4 The coefficient of determination for: **a** TPM times (*TP*, *TA*), **b** TPM coefficients (*WE*, *WW*, *WPD*, *UCD*) for M1 and M2. Source: own study (Mielczarek and Borkowski 2008)

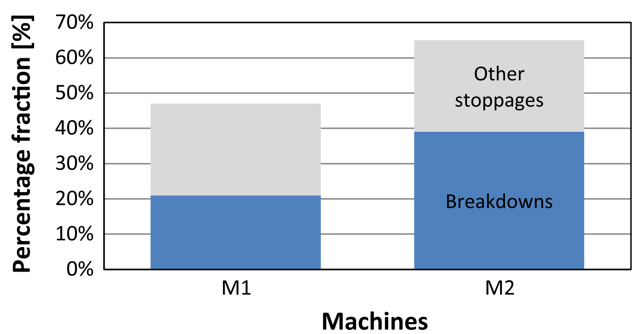

Fig. 5 The share of failures and other stoppages in the total downtime number for machine No 1 and machine No 2. Source: own study

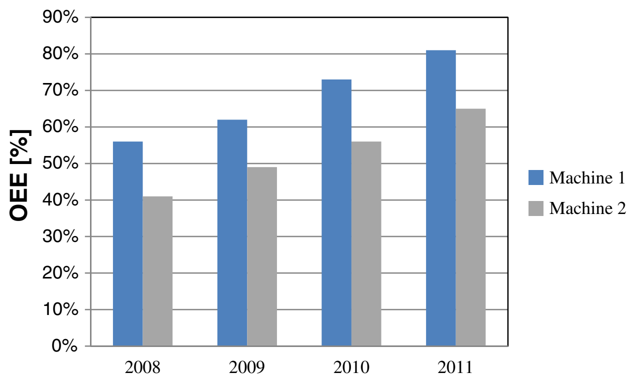

Fig. 6 The structure of OEE in the analyzed company for both machines (M1 and M2) in the research period 2008–2011. Source: own study

The results of the research finding analysis show that in 2008 a machine with a higher modernity degree (machine M1) worked effectively only 56 % of its time to achieve good-quality goods, while machine M2 worked effectively 41 % of its time. In the case of both analyzed machines (M1 and M2), an increase in the OEE coefficient in the research period 2008–2011 can be observed. The level of OEE for machine M1 and machine M2 in 2011 amounted to 81 % (M1) and 65 % (M2). None of the analyzed machines reached the desired level, which according to the world class should be a value of above 85 %. It is satisfactory that the OEE level is on the increase.

Conclusion

The analysis of examinations results shows that regardless of the machines' modernity degree, comprehensive maintenance of machinery in the company significantly improves the functioning of the entire production process and results in a good final casting quality level.

An analysis of research findings shows that in both analyzed cases, analyzed TPM coefficients (TP, TA, EC, WW, WPD) largely determine the quality of castings. There is a strong positive correlation between the level of non-conformities and downtime and breakdown times for both analyzed machines. Development of the remaining coefficients depends on the modernity level of the casting machine. The useful operating time significantly affects the quality only in the case of machine M2, due to the large differences between the ideal and the real-time implementation of a single piece casting. In the case of machine M1, which is a newer machine and the more automated a greater impact on quality have downtime (TP), breakdown time (TA) and coefficient of operating (WE) and in the case of machine M 2 there are some critical coefficients, such as: WW, WPD, UCD. UCD coefficient in the case of machine M1 does not significantly affect the occurrence of non-conforming product.

Research results support with useful information the foundry industry that supplies the motorway industry, since the appropriate casting quality level is important because of its safety importance in the final product—the vehicle. Machine maintenance has a great influence on the product quality, especially in the foundry industry. It should be noted that the result of the production processes should ensure the appropriate safety product level, which results from the quality level ensuring that the production process is supported by total productive maintenance.

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