

AN IMPLEMENTATION OF INFRARED THERMOGRAPHY IN MAINTENANCE PLANS WITHIN A WORLD CLASS MANUFACTURING STRATEGY

by

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The objective of the paper is to show the implementation of infrared thermography within world class manufacturing maintenance strategy. The results from infrared thermography inspections in a food processing and packaging solutions company were presented. Applicability of the infrared thermography, during a two-year period, caused a substantial reduction of the potential breakdown in the pilot area. Upon feasibility confirmation, the proposed method was spread to other production equipment of the company.

Key words: infrared thermography, condition monitoring, maintenance, world class manufacturing

Introduction

The global maintenance strategy encompasses the process of constant change and adaptation due to increasing demands, technical development, and modifications of management strategies in companies [1, 2]. The initial approach of the problem-oriented maintenance, targeted at the elimination of various problems, has recently been generally replaced by the process-oriented maintenance strategy. Its main objective is prevention as a substitution for traditional corrective activities. The traditional, event-based breakdown maintenance is now just a supporting element of the modern maintenance strategies. The majority of maintenance activities have been replaced by the time-based preventive maintenance (PM), and especially with a condition-based preventive maintenance approach, also known as condition-based maintenance (CBM) [3, 4].

During the last few decades, more attention has been given to the maintenance of technical systems. The reasons are numerous; first of all – the health and safety of employees, then energy consumption, environmental protection and, naturally, an increase of total profit through optimal management of maintenance costs.

The term world class manufacturing (WCM) was first used by Hayes and Wheelwright in 1984. Since then, the concept has been embraced, expanded, and enhanced by a number of authors, who have reinforced some of Hayes and Wheelwright's ideas, adding some new practices and ignoring others [5]. WCM is a concept of manufacturing strategy created in the United States and successfully implemented in Japanese industry during the early eighties of the 20th century [6]. It was created as the evolution of total productive maintenance (TPM). Its final ob-

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jective is a production system that operates based on just-in-time (JIT) production and total quality management (TQM) principles [7]. WCM brings about changes to the management strategy, especially at an operational level, which is considered to be crucial for a company. This concept provides a system of continuous improvement through the application of systematic and practical methodologies based on facts and calculations by transparent and visual means. It includes all employees: from workers at a production level, up to top management [8].

All segments of factory performance are improved through the WCM concept. Improvement of human resources is realized through changes in way of thinking regarding equipment and quality management and through constant training and education in order to upgrade the general and specific knowledge level of every employee as much as possible [7]. Equipment performances improvement is achieved through increasing of its efficiency resulted from implementation of advanced and intensive maintenance and early equipment management activities. It means that there are no rejections at the beginning of the production, maintaining the highest quality – “the first time is good”. By changing the “working culture”, in relation to employees' attitude to work, the improvement of efficiency of the whole factory can be achieved. The key point is to develop a flexible organization that constantly aspires towards increased knowledge and improvements, whereby, using not only engineers and managers, but all of its available manpower [9].

The fact that some authors [10] took a step further by defining a new phrase – world class maintenance, speaks in favour of the importance of maintenance. At the core of world class maintenance there is a new partnership among manufacturing or production people, maintenance engineering, and technical services in order to improve overall equipment effectiveness (OEE). It is a program of zero breakdowns and zero defects aimed at improving or eliminating losses.

Preventive maintenance

Maintenance represents one of the most important pillars for a company that operates within the WCM strategy. Generally, the PM program is applied for equipment which directly affects workplace safety, continuous flow production, and energy efficiency. PM is a maintenance policy in which selected physical parameters associated with an operating machine are measured and recorded, intermittently or continuously, for the purpose of analyzing, comparing and displaying data and information obtained to support decisions, related to the operation and maintenance of the machine [11]. It can be disaggregated into two specific sub-categories:

- statistical-based PM (the information generated from all breakdowns facilitates development of statistical models for predicting failure and thus enables the development of a preventive maintenance policy), and
- condition-based PM, *i. e.* condition-based maintenance (CBM) (CBM is the application of various technologies and methods in order to determine the current condition of machinery).

CBM is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. CBM attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviours. If properly established and effectively implemented, a CBM program can significantly reduce the maintenance cost by reducing the number of unnecessary scheduled PM activities. As shown in fig. 1, a CBM program consists of three key steps [12]:



Figure 1. Three steps in a CBM program

- data acquisition step (information collecting), to obtain data relevant to system health,

- data processing step (information handling), to handle and analyze data or signals collected in step 1, for better understanding and interpretation of data, and
- maintenance decision making step, to recommend efficient maintenance policies.

The main goal of CBM is to discover and prevent potential breakdowns. This is accomplished by measuring diagnostic parameters and then, based on certain criteria, a conclusion is made on whether they are within allowed limits or not.

The most prevalent methods of condition monitoring are those based on [11, 13]:

- measuring and analysis of vibrations,
- monitoring of thermal condition (IR thermography), and
- oil and wear particle analysis.

As a precondition for good implementation of CBM within the WCM concept, it is necessary to have equipment for machine condition diagnostics, such as instruments for the measurement of vibration levels, infrared (IR) thermography cameras and instruments for oil and wear particle analysis. Using these instruments for continuous monitoring, continual evaluation of the causes of production equipment breakdowns can be done.

Introduction to IR thermography and its applications

Any object at a temperature above absolute zero ($-273\text{ }^{\circ}\text{C}$) emits electromagnetic radiation in the form of rays which fall into the IR portion of the electromagnetic spectrum (from 1 to 1000 μm). IR thermography is a non-contact, non-intrusive technique, which enables us to see thermal energy. The energy emitted by a body is mainly a function of its surface temperature, so IR thermography may be considered as a two-dimensional technique of temperature measurement [14].

IR thermography basically includes a camera, equipped with a series of changeable optics, and a computer. The core of the camera is the infrared detector, which absorbs the IR energy emitted by the object and converts it into electrical voltage or current. Any object emits energy proportional to its surface temperature. In fact, IR thermography converts the energy radiated from objects in the IR band of the electromagnetic spectrum into a visible image, where each energy level may be represented by a colour, or a grey level.

The IR thermography, as a non-contact temperature measurement method, is widely used for: the measurement of the heat loss of buildings [15, 16], calculation of potential heat generated waste in production processes [17, 18], detection of defects, cracks, splits or other disturbances in a material [19], visualisation of heat developed in friction surfaces [20, 21], inspection of energetic installations [22], the determination of thermal stress of machines [23], *etc.* IR thermography is also used in medicine, insurance companies, product quality inspection, *etc.*

As a diagnostic method for condition monitoring of industrial equipment, the IR thermography gains more significance within the PM strategy. Additionally, development of portable IR cameras, available to a large number of users, has influenced the fact that the IR thermography inspection becomes (together with the vibrodiagnostic method) the main activity for the diagnostics of technical systems within a CBM. Using this method, the whole range of potential breakdowns of a technical system could be detected without the need to interrupt the production process. Therefore, the maintenance personnel can plan their work by knowing in advance their priorities, thus, minimizing the need for troubleshooting, allowing them to organize the appropriate manpower, get the necessary materials and shorten the repair time.

IR thermography investigation results and discussion

This study examines the implementation of the IR thermography inspection within the WCM strategy in a Serbian food processing and packaging solutions company. The company is

part of a large multinational enterprise which generally adopts the same approach to business policy within all of its facilities in the world.

The IR thermography testing methodology has mostly been determined by the WCM strategy which is implemented in a company. According to the recommendations by the WCM strategy, a specific equipment or part of the production zone (declared as the "pilot area") is usually chosen, at which point it is estimated that the application of a new method (in this case, IR thermography in maintenance plans) could provide the most appropriate information on the effectiveness and benefits of the proposed method. The effectiveness of the proposed method in the pilot area is assessed through a set of key performance indicators (KPI). After the feasibility confirmation in the pilot area, the application of the proposed method gradually spreads to other equipment and other parts of the production zone.

The IR thermography investigation in the company was realized during a two-year period. The company engaged an external service for the IR thermography investigations. During the 1st year, the so called "pilot project" of the IR thermography investigations was launched in the facility for PVC-paper packaging production – the pilot area. The objective of the investigation was to define the present condition of a group of different technical systems. The obtained information was the basis for further investigations and the main reference to determine whether specific changes or problems occur as well as to give suggestions to readjustment of critical points.

The measurements were realized with two types of IR cameras:

- the Infrared Solutions IK 21 IR camera based on a scanner sensor with 120×120 pixels resolution; with noise-equivalent temperature difference (NEDT) <0.4 °C at 30 °C; a spectral range 8 to 14 μm ; temperature range 0 to 350 °C; accuracy 2 °C or 2% of full scale; and operating temperature range 0 to 40 °C, and
- the Flir ThermaCAM P640 IR camera based on a focal plane array (FPA) uncooled micro-bolometer sensor with 640×480 pixels resolution; with NEDT <0.06 °C at 30 °C; spectral range 7.5 to 13 μm ; temperature range -40 to 500 °C in two ranges (optional up to 2000 °C); accuracy ± 2 °C or $\pm 2\%$ of reading; operating temperature range -15 to 50 °C.

For the analysis and quantification of differences in the thermography images, the following software applications were used: Snap View 2.1 (fig. 2) and ThermaCam Researcher.

The mechanical and electrical components suitable for non-contact, IR temperature measurements were included in this diagnostic and monitoring program. In most cases, electrical and electronic equipment was selected: transformers, switchgear, industrial fuses,

contactors, DC motors, *etc.* All measurements were performed under full-load and real operating conditions. The inspected equipment (70 measurement points) is shown in tab. 1.

The interpretation of the observed temperature differences ΔT [°C] from the anticipated values can be followed in the general guidelines presented in tab. 2 [24]. The previous experience, optimal load and component characteristics should also be taken into consideration while defining tolerability criteria. However, these rules should be used with caution, and before making a final decision one should take into account other factors such as safety, criticality, and reliability.

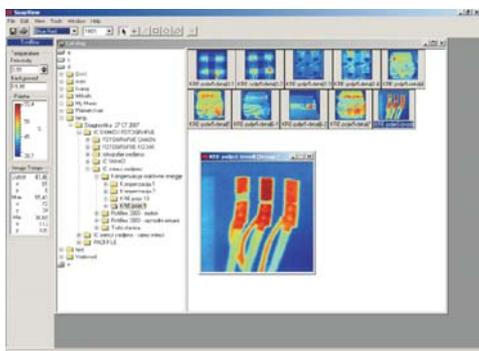


Figure 2. Software for the analysis of IR thermography images (IK 21 IR camera)

Table 1. Equipment covered within IR thermography investigation

No. of subset	Machine	No. of measurement points
1	Coating machine	21
2	Cooling station	8
3	Main power station	10
4	Compensation station	8
5	Printing machine	16
6	Shrinking tunnel	4
7	Transformers	3
TOTAL		70

Table 2. Guidelines for the observed temperature differences (ΔT) from the anticipated values

ΔT [°C]	The description of condition and recommended activities
1-10	NORMAL: There is a small possibility of physical damage. It is recommended to fix the problem during the next regular maintenance.
10-30	WARNING: There is a small possibility that there may be damage to nearby components. It is recommended to fix the problem in the near future; check load breakdown and adjust them accordingly; inspect for possible physical damage; check neighbouring components for physical damage.
>30	DANGER: Danger exists – needs immediate repair, if possible; replace the inspected component; carefully inspect all neighbouring components; perform a follow-up IR inspection after the repairs to ensure that no damage has been overlooked.

After a one year period, the investigations were repeated on the same samples. The obtained results from both measurements are shown in tab. 3. The results of the measurements gave answers concerning the need to introduce the IR thermography inspections into already existing maintenance plans. Furthermore, these inspections introduced new maintenance plans for other technical systems and equipment in the company. The IR thermography shows huge potential as a method which is applicable to a wide range of production equipment, installations, buildings, processes, *etc.*

Table 3. IR thermography investigation results

Year	Normal	Warning	Danger	No. of measured points
1 st year	43	17	10	70
2 nd year	62	7	1	70

In order to show what the levels of measured temperatures were, the printing machine subset will be explained in more detail. The printing machine lay-out is presented in fig. 3 with measuring points (T-thermography) and belonging temperatures (tab. 4). There are 16 measuring points identified: 6 measurement points at the DC motors and 10 measurement points at the electro cabinets.

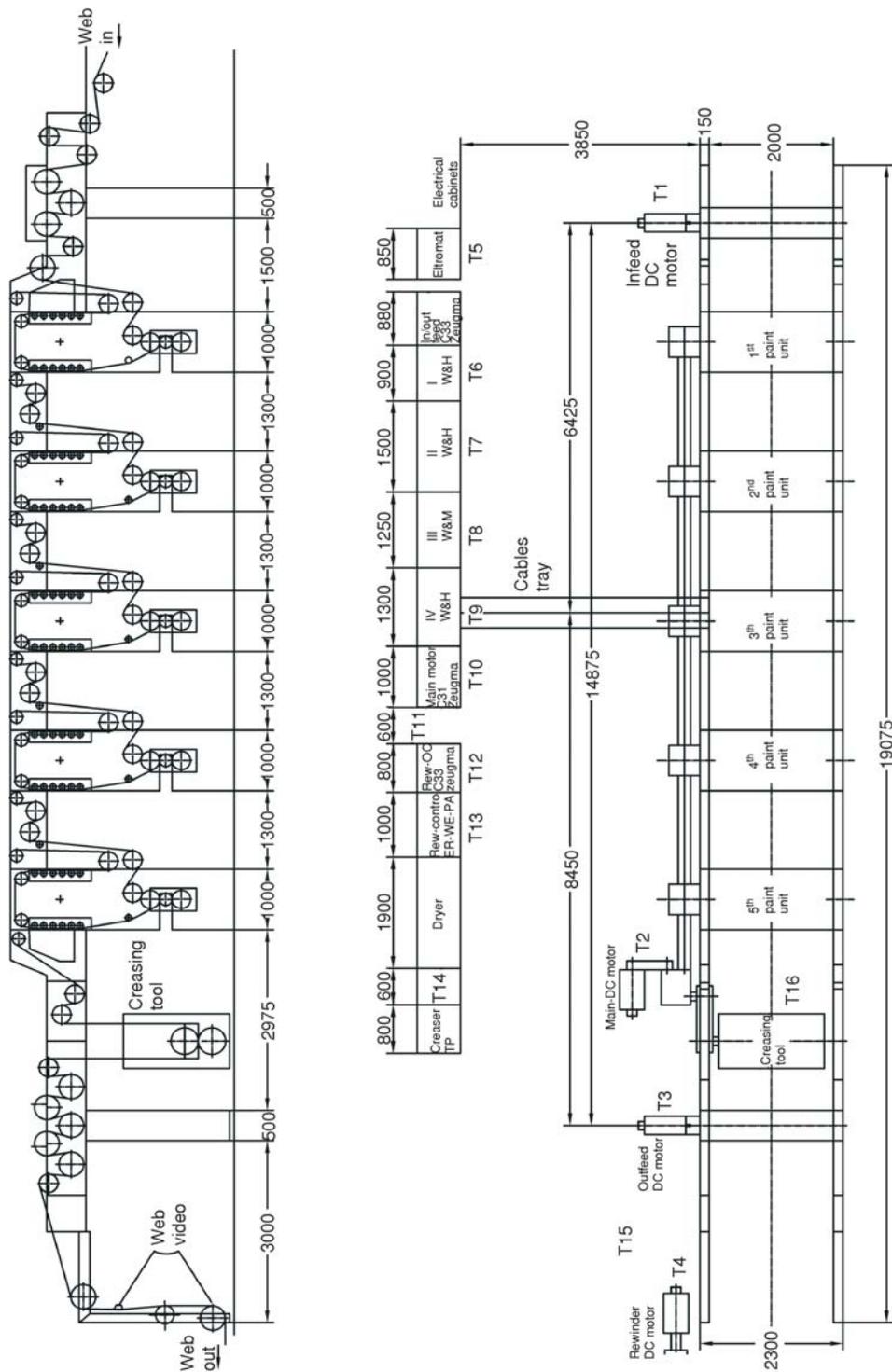


Figure 3. The layout of printing machine with the measuring points' positions (T1-T16)

Table 4. Temperatures on electro equipment of the printing machine

Measurement point	Printing machine			
	1 st year		2 nd year	
	T [°C]	Mark	T [°C]	Mark
T1	61.1	Normal	52.5	Normal
T2	53.2	Normal	52.5	Normal
T3	69.1	Warning	61.0	Normal
T4	58.6	Normal	58.7	Normal
T5	68.1	Warning	62.3	Normal
T6	52.5	Normal	52.8	Normal
T7	61.5	Normal	72.6	Warning
T8	65.2	Normal	76.5	Warning
T9	62.4	Normal	59.5	Normal
T10	61.8	Normal	57.8	Normal
T11	67.6	Warning	64.0	Normal
T12	120.4	Danger	62.3	Normal
T13	63.2	Warning	62.0	Normal
T14	41.3	Normal	40.7	Normal
T15	45.8	Normal	48.2	Normal
T16	53.6	Normal	52.8	Normal

The factors which can affect accuracy of the measurement results, shown in tab. 4, could be identified as: the selection of the emissivity coefficient, environment, technical specifications of the used camera, and the human factor. As already mentioned, the energy actually detected by the detector in the IR camera depends on the emissivity of the surface under measurement. The environment can affect the measuring result either through energy added as reflected by the surface of the surroundings, or through a portion of energy absorbed by the atmosphere between the camera and the object. The accuracy of the used IR camera is ± 2 °C or ± 2 % of the reading. Reducing the influence of the human factor on accuracy of measurement results can be minimized through theoretical and practical education of the involved personnel.

Previous analysis indicates that there are numerous factors that affect the accuracy of the measurement results shown in tab. 4. The temperature of some individual components and parts could be verified by the available and applicable contact measurement methods in order to provide verification of results from the IR thermography. In most cases the price of the observed component, is significantly lower than the cost of damage that may arise in the event of its failure. This implies that sometimes it is better to replace a suspicious element, with detected increased temperature (or take some other action to restore its condition) than to go into an in-depth analysis of the causes of its current state, represented by the increased temperature.

After the 1st year of inspection, a relatively large number of measurement points were marked as “danger”. For these points, urgent correction activities were specified for the elimination of the causes of the high temperature (poor contacts on the tested electric equipment were the cause). The necessary changes of components or reconstruction were realized, and the total condition during the second inspection was considerably more favourable.

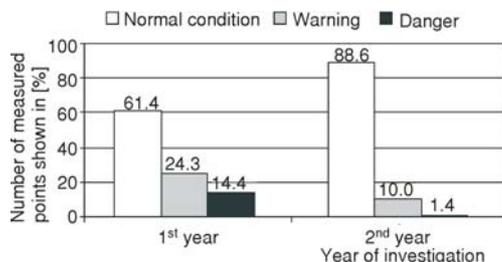


Figure 4. The structure of results on the measured points

From the 1st and 2nd year are given in fig. 4. It can be concluded that after the two-year period, the condition was significantly better in comparison to the beginning of testing, due to the activities that followed the first inspection. The number of dangerous points was reduced from 10, at the beginning, to only 1, which represents a 90% improvement.

Some representative IR thermography pictures are shown in figs. 5-7. A DC motor with corresponding IR thermography pictures (measurement point T3 from fig. 3 and tab. 4) are presented in fig. 5. In the 1st year, a small motor used for the cooling of a larger DC motor was indicated as the hot point of the system, so the whole system was marked with a “warning” label (fig. 5b). The Measurement in the 2nd year (fig. 5c) shows that the temperature did not increase, in comparison to the measurement from the 1st year, so this point is now labelled as “normal”.

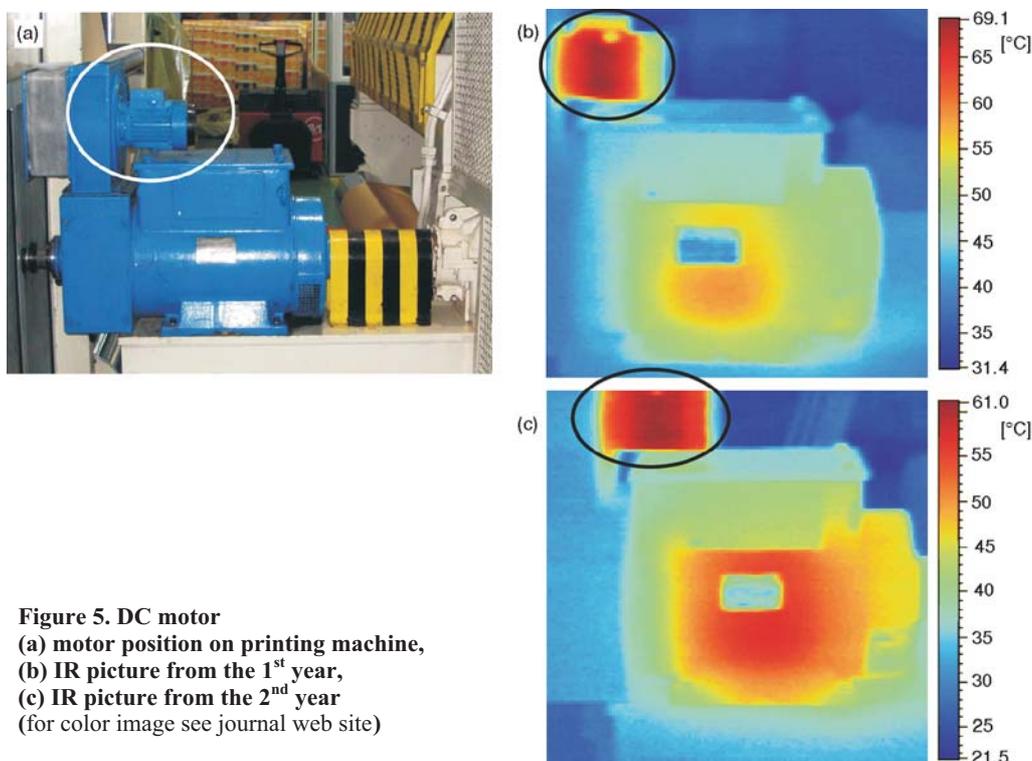


Figure 5. DC motor
(a) motor position on printing machine,
(b) IR picture from the 1st year,
(c) IR picture from the 2nd year
(for color image see journal web site)

The measurement points marked as “warning” need to be analyzed in more detail and monitored at a later period. For the majority of measurement points which had been marked as “warning” during the 1st year inspection, it was determined that the temperature increase did not occur within the observed zones during the 2nd year inspection. Therefore, for the 2nd year measurement they were marked with “normal” (as an example: points T11 and T13 in tab. 4).

The comparative presentation of the obtained results of IR thermography investigations

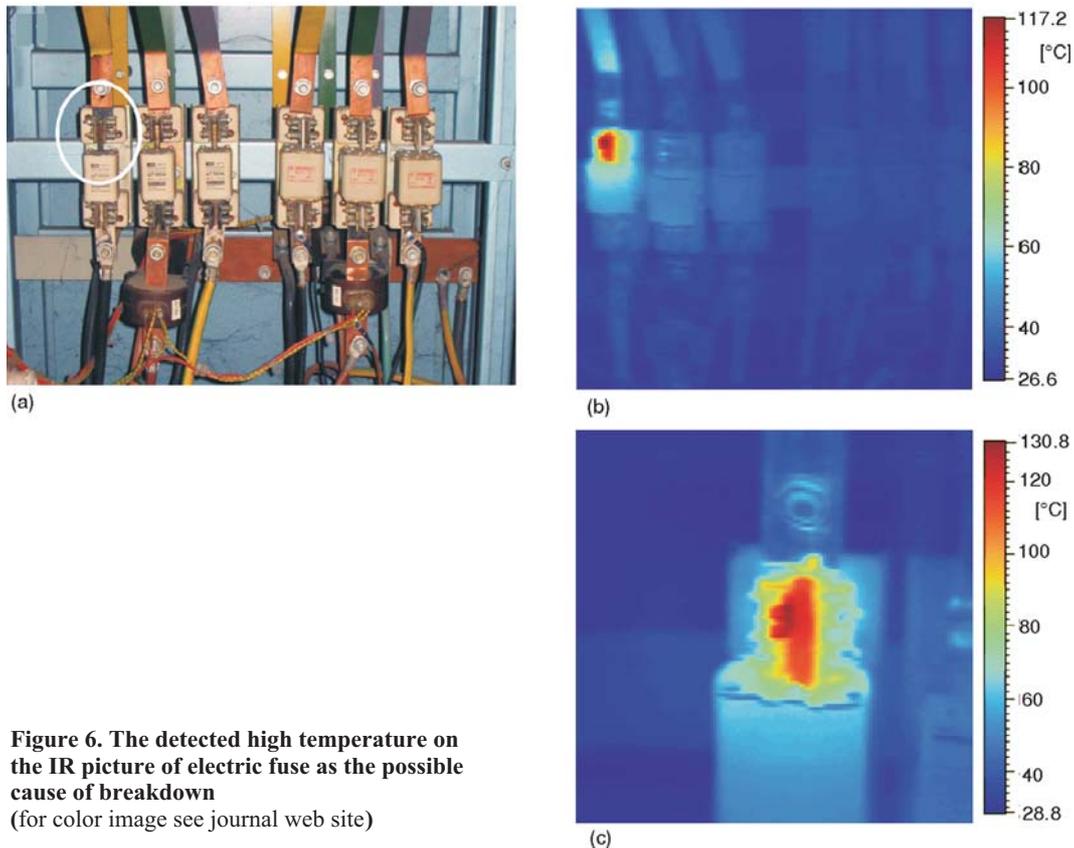


Figure 6. The detected high temperature on the IR picture of electric fuse as the possible cause of breakdown
(for color image see journal web site)

Figure 6, shows an IR thermography picture of six industrial electric fuses, captured in the 1st year of investigation. It can be seen that the electric fuse on the left is much warmer than the others, which means that there has been a poor contact or damage to the fuse which was a distinctive threat to the functioning of the technical system. At this point, emergency activities were carried out to resolve the causes of the increased temperature, and thus avoiding sudden breakdowns as well as material and financial damage.

In the 2nd year of investigation the same electric fuses were captured and one measurement marked as “danger” is shown in fig. 7(a). As can be seen, two fuses had a normal temperature, but there was found to be a new possible failure on the contact of the third electric fuse, which was replaced immediately. The maximum temperature on the fuse was about 352.3 °C which is significantly over the allowable limits.

Figure 7(b) shows the IR thermography pictures of an electro cabinet with the temperature of all components below 45 °C.

After successful implementation of the IR thermography inspections in the pilot area, where relevant results had been obtained and a significant improvement in the implemented CBM method had been realized, the factory management decided to spread IR thermography inspection to all other areas where it is possible to achieve savings in energy, improve safety, improve effectiveness, and reduce costs in general. The IR thermography inspection within WCM can be a very powerful tool against failures and in the monitoring of machine conditions, but

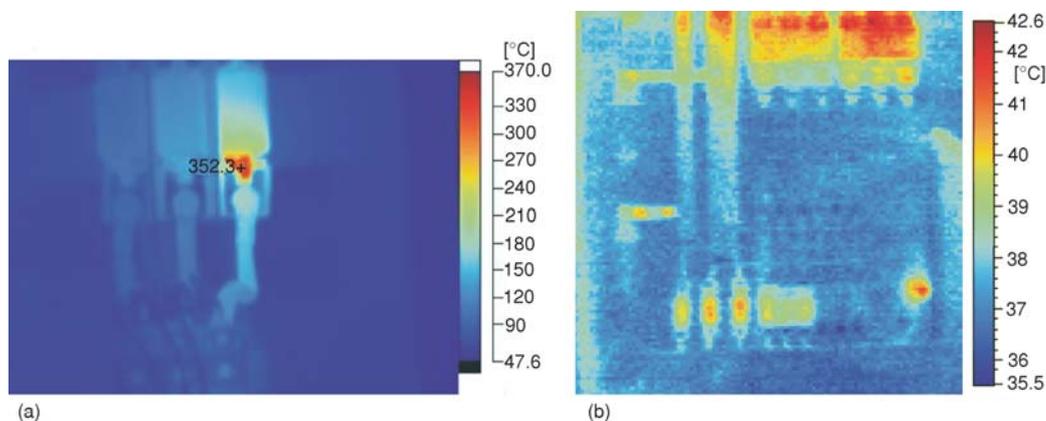


Figure 7. (a) The IR picture of electric fuse with extremely high temperature, (b) the IR picture of electro cabinets with low and uniform operating temperature

proper training of the maintenance worker should be given. Additionally, the company is equipped with a special area for training in order to minimize the human factors which can affect accuracy of the IR thermography measurement results.

Conclusions

Based on the analysis of IR thermography inspection in order to determine the potential breakdowns of production equipment, presented in the paper, one can conclude the following.

- Modern industrial environment strives for zero breakdown of production equipment which imposes the implementation of contemporary maintenance strategies, predominantly those based on CBM.
- The IR thermography inspection is the one of the most prevalent condition monitoring methods. During the equipment inspection, production equipment functions in real operation regimes and there is no need to interrupt the production process, which eliminates related costs.
- For the presented investigations, in a two-year period, the number of potential failure causes was lowered by 90% and the maintenance time and costs were decreased.
- Company policies consider all points with a "danger" label as a successfully prevented breakdown, and cost calculation is performed with the assumption that breakdowns at the points have occurred. Unfortunately, the cost reduction data are not available because the company considers it to be confidential information.
- The company is spreading the IR thermography to other areas where it is possible to achieve savings in energy, such as heating, ventilation, air-conditioning installations, and building inspections.

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