Thermal Processing Systems for Automotive Suppliers

Requirements for CQI-9 compliant automation

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In this essay, CQI-9 HTSA will be the guideline for discussing a number of special requirements the automotive industry places on industrial thermal processing equipment. The automotive industry's ultimate goal is a system that provides for continual improvement, emphasizing defect prevention (zero defects), and reduction of variation at lowest costs. Yet, it is left to the supplier's discretion how to achieve this goal, which will either be by organizational measures or in the form of special design of the thermal processing systems in use. The main topic in this article is automation systems for continuous industrial thermal processing systems, and how organizations supplying heat treated automotive parts can satisfy the automotive industry's highly specific demands.

The global automotive industry is hard to please. Every automaker expects its internal and external suppliers to deliver high quality products on time and at low prices. This applies in particular to suppliers of heat treated parts. Their aim is to reduce costs continually while also improving quality and, ultimately, to reach a "zero defect strategy". To assure this, the auto industry has developed a series of specific rules and regulations. Any external heat treatment company, hopeful of joining the supplier base, is expected to implement a certified QM system approved by the automotive industry, together with suitable automation of their thermal processing systems.

Automotive Industry Rules

In the past, the European and American automotive industries each introduced their own industry standards for quality management systems. The American automakers favoured QS-9000 [1], while German automakers embodied their standard in VDA 6.1 [2]. The common denominator between QS-9000 and VDA 6.1 was that they both placed enormous emphasis on planned and precautionary error prevention measures. Double-certifications could typically be avoided by obtaining ISO/TS 16949 [3] certification.

ISO/TS 16949:2002

ISO/TS 16949 [3] is a quality management standard of the automotive industry jointly developed by members of the International Automotive Task Force, or IATF (BMW Group, Daimler AG, Fiat Auto, Ford, General Motors, PSA, Renault, Volkswagen AG), with the intention to define global unified standards for a quality management system in the automotive industry.

The IATF member companies demanded ISO/TS 16949:2002 certification of at least the direct suppliers (tier 1). Without ISO/TS 16949:2002 certification, delivery to the above-named automakers is for the most part refused.

ISO/TS 16949:2002 itself is based on ISO 9001:2000 [4]. It was intended to supersede the existing national standards VDA 6.1 and QS-9000, and as of 2004, once the transition period had lapsed, become the worldwide basis for certification of QM systems in the automotive supplier industry. Today, an ISO/TS 16949 certified quality management system of a supplier of standard parts will be recognized as compliant to requirements by automakers and direct suppliers everywhere in the world. Yet, customer-specific requirements are already showing up again on top of ISO TS 16949.

The most important target of ISO/TS 16949:2002 is the development of a quality management system that provides for continual improvement. It particularly stresses error prevention and customer focus.

CQI-9 Special Process: Heat Treat System Assessment (HTSA)

The special standard named CQI-9 [5] that specifically addresses "Heat Treat System Assessment" (HTSA) was first issued by the Automotive Industry Action Group (AIAG) in March 2006. A second, revised edition entitled "Special Process: Heat Treat System Assessment" followed in 2007. AIAG is a lobby to which mostly, but not exclusively, North American automakers belong. Members of AIAG are OEMs such as Caterpillar, Chrysler, Daimler, Ford, GM, Honda, Nissan, Toyota and a large number of globally renowned suppliers.

The members of AIAG present CQI-9 as a companion document to ISO/TS 16949:2002. CQI-9 deals exclusively with heat treatment. While the above-mentioned "generally applicable standards" leave the issue open as to whether, when and how a special requirement must also be applied to heat treatment, CQI-9 is specific and for the most part explicit in this respect. These CQI-9 requirements can therefore be applied as a good starting basis and as a guideline for automotive industry requirements for assessment of thermal processing systems.

Automotive Industry Requirements for Thermal Processing Systems

As a general rule, there is nothing in the automotive industry requirements, such as in CQI-9, stating how a requirement must be implemented. It is left to the discretion of the thermal processing system operator to implement the requirements either by organizational measures or in the form of special requirements for control or computerization of the thermal processing systems in use. The general rule, however, is that producers of thermal processing systems and protective gas generators must have suitable computer-assisted monitoring systems (e.g. PLC) with alarm functions and alarm logs. These systems are then also suitable for proving conformity [5].

Process Control Plan

It is fundamental and a mandatory prerequisite for a "zero defect strategy" that heat treatment is identified as a manufacturing process that can be controlled at any time, even if it is a special process. The process control this demands is pro-active, process-oriented controlling of all technical and application-specific functions required for being able to perform the heat treatment reliably and smoothly. The aim of this process control is to identify problem situations as early as possible, or to solve them before they become critical to the heat treatment process, and also to ensure that the actual processes are going to plan.

A thermal processing system is a complex entity. Influencing variables in the system (such as the process) can have a greater or lesser impact depending on their nature. Only if the process remains within the limits defined in the specification[1] the product quality will satisfy the requirements. Deliberate or accidental changes to the many different influencing variables can negatively affect the process quality. The process control plan should therefore ensure that the parts quality in the actual manufacturing process does meet the requirements. This demands both organizational approaches and technical measures.

A distinct process control plan must be created for each part or each family of parts [5]. In practice, the process control plan consists of function-specific databases and of organization or work instructions. Databases and organization instructions are cross-referenced in the process control plan. Examples of function-specific databases would be the parts database described below and the recipe databases.

The process control plan contains set points that can typically be preset automatically from the parts database, as well as the product features that must be manually verified and statistically controlled. The process control plan must also contain the testing intervals and the sample size of the product features to be tested. For continuous and linked batch systems at least, this means it is advisable to link the samples to the batch respectively lot tracing as well.

Parts Database

Fig. 1 shows the parts database of a belt furnace hardening and tempering furnace plant. The set points are specified for each part. Treatment parameters for families of parts, e.g. the temperature set points in a hardening or tempering furnace, are summarized in recipes. Part-specific set points such as vibration intensity of the vibrating belt are individually preset.

Recipe Management and Automatic Recipe Changing

CQI-9 addresses the use of recipes explicitly [5]. The term "recipe" is used if a computer system, e.g. PLC, presets the process parameters according to a key term such as a part number. Uniform parts or families of parts should be reproducibly heat treated at consistently the same set points. Set points are process temperatures, throughput times, C-levels or the circulation volume in the hardening bath, for example. Adherence to the set points must therefore be monitored within the operating tolerances [5].

Automatic recipe change is a well tried and proven practice. Changes to the process parameters are automatically made by the control system depending on the electronic lot tracing. Lot gaps will be calculated where necessary. This reliably prevents manual errors. Modern automation systems allow several simultaneous recipe changes within a belt furnace system. In the early days of process automation, automatic recipe

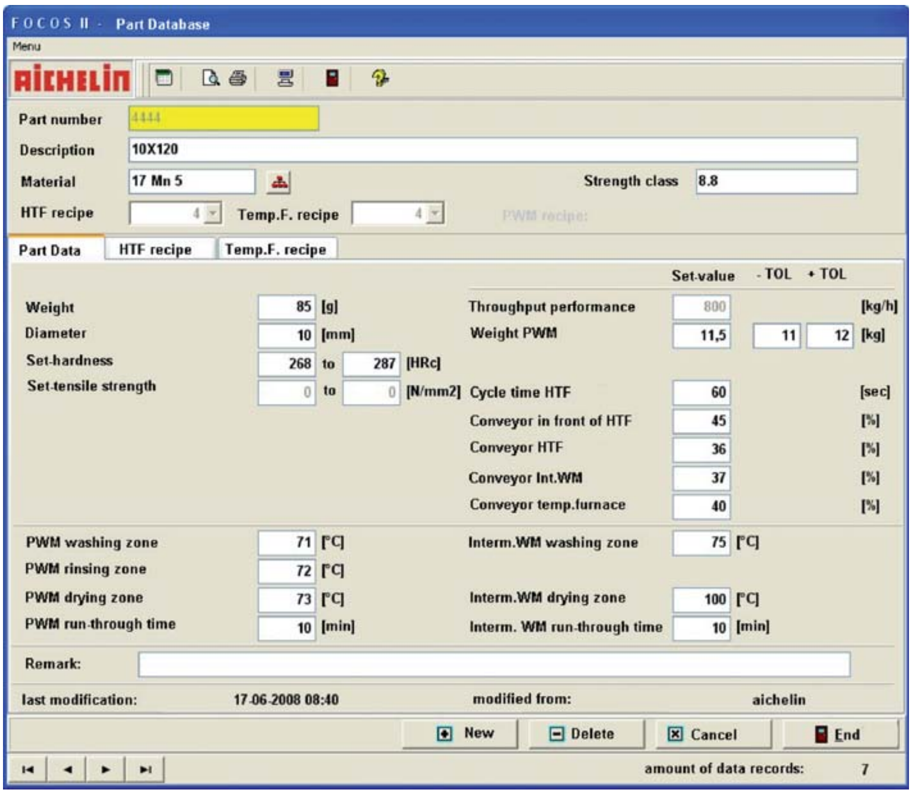

Fig. 1: Parts database of a belt furnace

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1 We use the term specification here to describe all technical requirements and other requirements placed on the part by the manufacturer and/or customer.

change still required a process computer [6]. Today, significantly more powerful PLCs assume this duty.

Fault messages that arise during a recipe change are only attributed to the batches influenced by the fault on the basis of the electronic lot tracing.

Set point changes must of course be documented as well. The recipe management should therefore also include version control and a where-used list for a selected recipe.

Proof of Process Capability

Statistical process control (SPC) is the answer to the question "how well is the process managed?" The essential difference from traditional quality assurance methods that recognize quality deficiencies in the final product is that, using statistical methods, quality deficiencies should already be prevented in the manufacturing process (zero defect target). The use of statistical methods is therefore another central requirement the auto industry places on serial parts suppliers [3].

Proof of process capability must be brought over a long period of time. Random samples are taken at regular intervals from a running process and quality characteristics measured. The result of the random samples is rounded up to the parent population. It is known that distributions in industrial production frequently obey a normal distribution curve, known as a Gaussian error distribution curve, to sufficient accuracy. This applies then to the entire population and to the random samples taken.

Process capability is associated with important product characteristics, such as the tensile strength of a fastening element. The process capability index reveals to what (statistical) certainty a specified product characteristic can be achieved. The higher the process capability index, the greater the certainty that the entire production resides within the specification. While the process capability index Cp only informs us of the estimated distribution, the index Cpk also takes into account the relative position of the mean value to the tolerance limits. The auto industry frequently aspires to a distribution spread (Cp value) of ±6 standard deviations, often called "Six Sigma (6σ)", together with a distance of 1.5 (Cpk value) of the process mean from the closest tolerance limit. At a Six Sigma level, the probability of an error occurring is still only 3.4 errors per million potential errors, i.e. the probability that the process is error-free is 99.9999981%.

There are many influences on the product characteristics typically referenced for measuring process capability in the case of heat treatment, such as tensile strength. These influences include the geometric shape of the part, the media used (e.g. hardening oil), the loading and the "machine capability" of the thermal processing system. Results obtained from a heat-treated part are always influenced by the part itself as well, and are only very difficult to separate from the heat treatment performed after completion of the heat treatment [7]. The manufacturer of a heat treatment system can at best influence the process capability by influencing the machine capability of the thermal processing system.

Machine Capability of Thermal Processing Systems

Machine capability is an important influencing variable on process capability. With machine tools for example, machine capability typically describes the quality capability of a machine under ideal conditions. In a machine capability study, a random sample of at least 50 pieces is usually taken from ongoing production. Machine capability is therefore short-term capability under ideal conditions. Often, machine capability is determined as a step in the acceptance of new machines or following revision work.

Machine capability, which is designated analogously to process capability as Cm and Cmk, is proven as a way to assure that the machines used are capable of performing the processes at the necessary accuracy, repeatability and comparability.

In thermal processing systems, this approach cannot be employed, since the production parts are merged into lots respectively batches, or because the throughput time for the thermal process is too long, for example.

Sommer et al. [8] therefore recommend, for good reason, making a distinction between the process capability of a heat treatment system and the process capability of components. It makes sense, therefore, to define relevant system-specific process parameters and to specify objectively measurable tolerance limits for these. While this system capability would serve as an acceptance and assessment criterion for the system and process control, it does not guarantee any capability criterion for the results in the form of parts or batches.

One practically proven acceptance criterion for thermal processing systems is temperature uniformity as defined in DIN 17052-1 [9]. This assumes that if the temperature bandwidth in the empty furnace lies within specified limits (called quality classes A, B or C), then the result in the form of the product will also exhibit no inadmissible deviations. This is why CQI-9 prescribes annual verification of temperature uniformity [5]. Temperature uniformity, however, cannot be continuously monitored. As a result, it is also not suitable for controlling machine capability.

Parameters from which online machine capability parameters can be derived using SPC methods could be the loading (weight per weighed-in quantity), throughput time (time in furnace), temperature deviation, C-level deviation, furnace pressure, process gas quantities, hardening medium circulation, residing time in hardening medium, etc. [10, 11], the more so since all of the above parameters have to be assigned operating tolerances [5]. Which of the abovementioned parameters is best suited to be an indicator for machine capability depends, however, on both the product and the process [11]. All in all, there is still much research and standardization that has to be done with regard to machine capability of thermal processing systems.

Errors or Faults

The questions of potential causes of error and potential resulting defects are the core questions when looking for a comprehensive "zero defect strategy". The answers to these questions will then allow analysis of the consequences of the fault, so that it can be decided what structural or planned preventative measures will need to be taken for which potential faults so that no defects in the product arise.

The origin of errors is deviations from the nominal conditions. These deviations usually occur due to external influences or due to wear. Accordingly, the

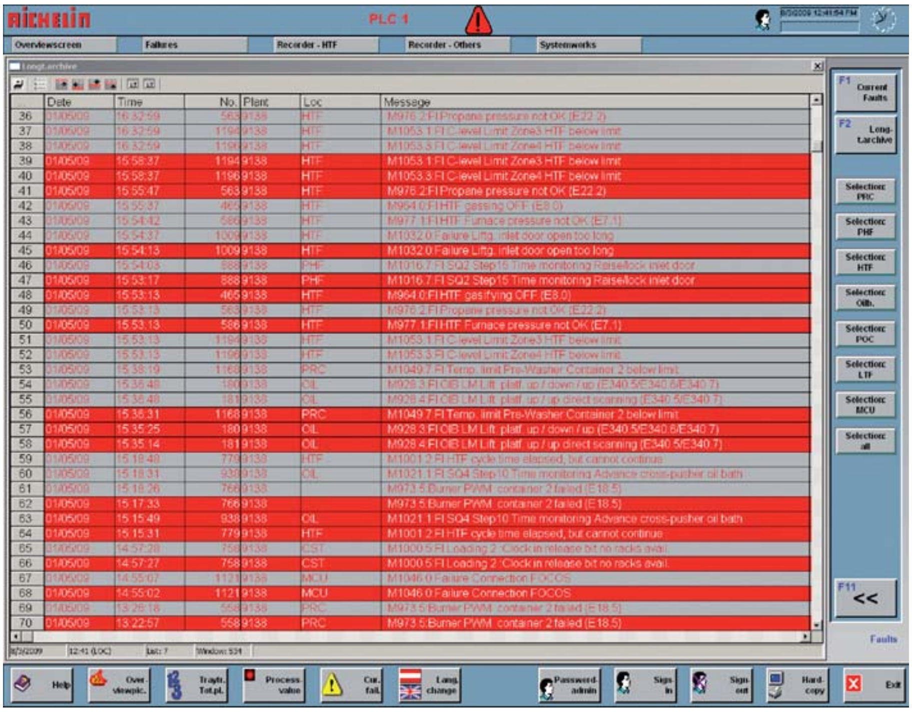


Fig. 2: Error message system

seriousness of an error also increases over time [12].

Defective products must be rejected [3]! The "zero defect strategy" prescribed by the auto industry leaves little other choice. Since this cannot be done immediately in a closed furnace, for example, affected lots must be tagged in the electronic batch tracing and rejected at the next suitable position. Alarm processing and electronic batch tracing must be appropriately linked up to do this work. Accordingly, there should be a way of attributing priorities as well as a fault location to fault messages [12].

Fig. 2 shows the fault archive of a modern process control system. Each fault message contains the date, time, system, fault location in the system, priority and text message.

But not all faults are equal! The magnitudes and consequences can be very different. Accordingly, it should be possible to add comments to fault messages so that the effects can be traced later on.

Fault messages must be checked regularly and the checks recorded [5]. For very important fault messages (e.g. over/undertemperature or emergency stop), it is best if a self-check is implemented.

Process Monitoring Instructions

For economical or technical reasons, usually not all potential causes of error can be automatically detected and reported. These potential causes of error without monitoring sensors must be inspected and recorded by the operator according to the process monitoring instructions.

The operator observes the process according to his experience. He can visually observe the process only to a very limited degree. The more automated heat treatment systems become these days, the less he can directly see, smell or hear. Ultimately, he can only draw conclusions about deviations in the process from measurements.

Typical measurements that are necessary for avoiding potential causes of error could be, for example, the foil test for C-level comparison or comparative temperature measurements with a certified thermocouple and subsequent input of an offset, as described in the chapter on Maintenance.

Support from Diagnostic Systems

If the system is equipped with a diagnostic system, then the duration of a fault can be shortened, since the time taken to find the error can be eliminated, or at least shortened [12].

The time slices for eliminating a fault are illustrated in **Fig. 3**. It becomes clear that a significant portion of the time taken to eliminate a fault consists of diagnostic time.

Working from the overview screen, the maintenance engineer can swap to the respective diagnosis screen of the subordinate hardware level to gain information on the diagnostic status of individual system areas or components. If a fault is signalized in the overview screen, then he can quickly access the diagnostic module of the affected component.

It is important to diagnose causes and eliminate faults as quickly as possible, since the longer the fault remains unfixed, the greater are the effects on the process and the heat treated products [12].

Error Statistics

A prerequisite for a successful zero defect strategy is to avoid systematic errors or weak points. Errors should never be regarded as something normal or unavoidable. Systematic errors must be permanently eliminated. Statistical analyses can be a very helpful tool for doing so.

Error statistics contain information about the type, duration, frequency and cause of errors. Error statistics are a good tool for recognizing weak points. Error statistics can also be used to increase the amount of information on operating resources or components. The scope and times of maintenance mea-

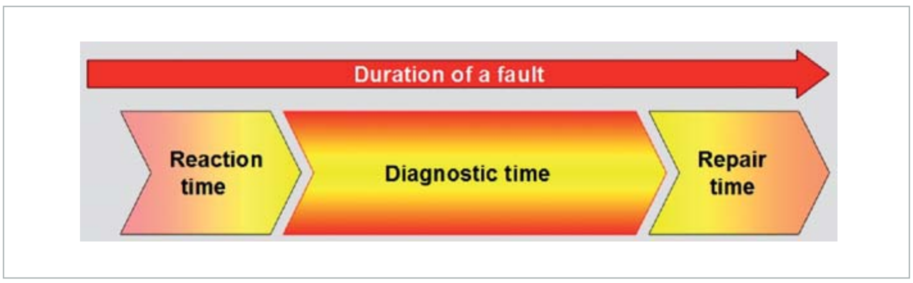


Fig. 3: Time slices required for elimination of a fault

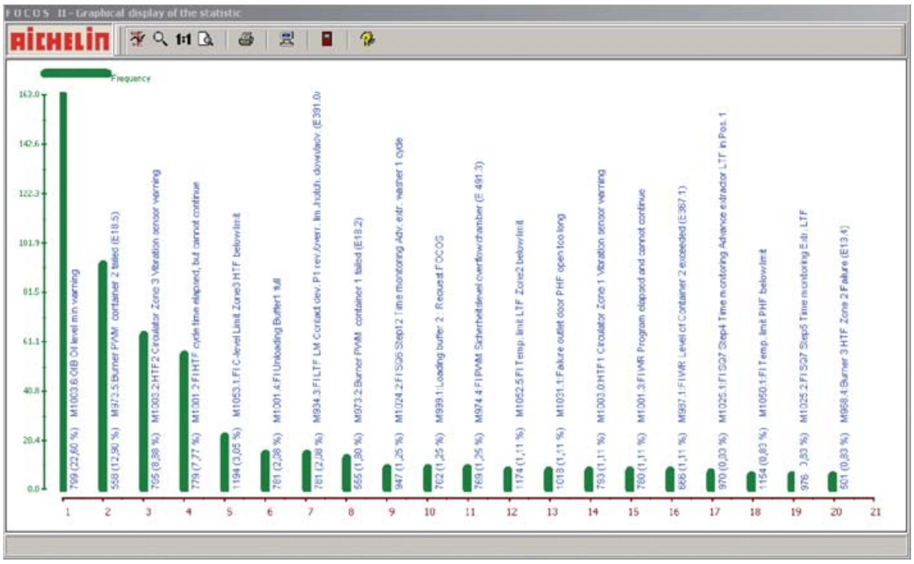


Fig. 4: Error statistics

sures, for example, can also be oriented on the frequency or duration of errors [13].

Fig. 4 illustrates some error statistics. Errors can be evaluated according to frequency as well as duration.

The causes of chronic errors can be localized by using statistics, and then permanently eliminated. This minimizes maintenance and repair times, which in turn leads to increased utilization and better availability.

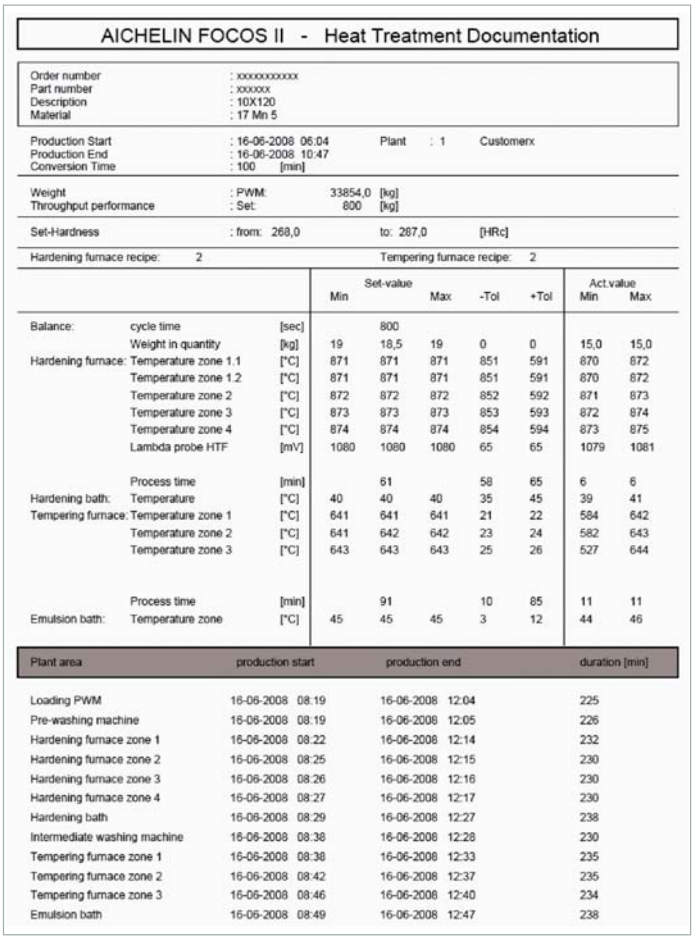
Prevention of Mixing

The uncontrolled mixing of defective products or different batches must be avoided at all costs [1, 3].

Batch tracing, in particular the tracing of lot start and end, is done purely electronically by the PLC these days. Electronic lot tracing works very precisely, so that the gap during a lot change can be kept as small as possible, and thereby adjustment times greatly reduced [13].

However, some continuous heat treatment systems, in particular belt furnaces for hardening and tempering fasteners, contain areas that involve a risk of mixing parts. Examples of this are non-positively driven parts feed mechanisms, and vibration conveyors or bunkers in particular.

It is mandatory to monitor such areas when changing products [5]. Acknowledgement keys on the loading hopper and all transition points are an optional measure that additionally secures an automated product change. Enabling of the acknowledgement keys must depend on the electronic lot tracing, i.e. only once the gap has reached a transition involving a risk of mixing can an acknowledgement be made. In the case of vibration conveyors, they must also be switched to higher feed rate for type separation.



AICHELIN FOCOS II - Heat Treatment Documentation

Order number	: xxxxxxxxxxx
Part number	: xxxxxx
Description	: 10X120
Material	: 17 Mn 5
Production Start	: 16-06-2008 06:04 — Plant : 1 — Customerx
Production End	: 16-06-2008 10:47
Conversion Time	: 100 [min]
Weight	: PWM: 33854,0 [kg]
Throughput performance	: Set: 800 [kg]
Set-Hardness	: from: 268,0 to: 287,0 [HRc]
Hardening furnace recipe: 2	Tempering furnace recipe: 2

			Set-value Min		Max	-Tol	+Tol	Act.value Min	Max
Balance:	cycle time	[sec]		800					
	Weight in quantity	[kg]	19	18,5	19	0	0	15,0	15,0
Hardening furnace:	Temperature zone 1.1	[°C]	871	871	871	851	591	870	872
	Temperature zone 1.2	[°C]	871	871	871	851	591	870	872
	Temperature zone 2	[°C]	872	872	872	852	592	871	873
	Temperature zone 3	[°C]	873	873	873	853	593	872	874
	Temperature zone 4	[°C]	874	874	874	854	594	873	875
	Lambda probe HTF	[mV]	1080	1080	1080	65	65	1079	1081
	Process time	[min]		61		58	65	6	6
Hardening bath:	Temperature	[°C]	40	40	40	35	45	39	41
Tempering furnace:	Temperature zone 1	[°C]	641	641	641	21	22	584	642
	Temperature zone 2	[°C]	641	642	642	23	24	582	643
	Temperature zone 3	[°C]	643	643	643	25	26	527	644
	Process time	[min]		91		10	85	11	11
Emulsion bath:	Temperature zone	[°C]	45	45	45	3	12	44	46

Plant area	production start	production end	duration [min]
Loading PWM	16-06-2008 08:19	16-06-2008 12:04	225
Pre-washing machine	16-06-2008 08:19	16-06-2008 12:05	226
Hardening furnace zone 1	16-06-2008 08:22	16-06-2008 12:14	232
Hardening furnace zone 2	16-06-2008 08:25	16-06-2008 12:15	230
Hardening furnace zone 3	16-06-2008 08:26	16-06-2008 12:16	230
Hardening furnace zone 4	16-06-2008 08:27	16-06-2008 12:17	230
Hardening bath	16-06-2008 08:29	16-06-2008 12:27	238
Intermediate washing machine	16-06-2008 08:38	16-06-2008 12:28	230
Tempering furnace zone 1	16-06-2008 08:38	16-06-2008 12:33	235
Tempering furnace zone 2	16-06-2008 08:42	16-06-2008 12:37	235
Tempering furnace zone 3	16-06-2008 08:46	16-06-2008 12:40	234
Emulsion bath	16-06-2008 08:49	16-06-2008 12:47	238

Fig. 5: Heat Treatment Proof Certificate

Product Traceability

For the most part, documentation of heat treated parts for the automotive industry is mandatory. The obligation to keep records applies, for example, to all parts that significantly influence the vehicle safety or the adherence to legal specifications. These parts must be traceable[2].

The labeling and traceability of products is a core requirement of the automotive industry [3]! A suitable system must be implemented to ensure that, if ever needed, the quality records can be matched to the parts. The traceability system must make it possible to prove that due care had been taken if there is a case of damage (dislot from liability).

To enable this, the heat treatment must take place in traceable batches. For each batch, there must be some kind of verification document that can be linked to all relevant information. The traceability must be managed in a way that positive

2 Product traceability refers to the possibility of determining at any time where, when and by whom a product has been obtained, manufactured, processed, stored, transported, used and disposed of.

tracing to the production and test batches is guaranteed [5]. The Heat Treatment Proof Certificate, shown in **Fig. 5**, complies with this requirement. The Heat Treatment Proof Certificate is a summarized document that shows the order data (order number, part number…), duration of heat treatment (start time, end time and duration in the individual treatment zones), and the nominal and actual values. If any quality-relevant faults have occurred, then they will also be shown in the certificate.

Features that require mandatory recording are prescribed by the automotive industry, e.g. in VDA Volume 1 "Quality Evidence" [2]. For thermal processing systems, these process-substantiating records typically concern the parameters of the furnace atmosphere, i.e. temperatures, C-level and retention times [5], as well as cycle times and weighed-in quantities.

Quality evidence includes long-term archiving of the Heat Treatment Proof Certificates. As a rule, compulsory period of record-keeping is explicitly agreed. Frequently, Heat Treatment Proof Certificates must be kept for 15 years.

Trend Displays

It is natural and inevitable that a production process will not always run the same. Rather, it will vary within the tolerances. Continuous records of actual values are therefore imperative [5, 3].

Continuous trend displays of important process parameters, such as the temperature or C-level curves shown in Figure 6 for a multipurpose chamber furnace, can deliver important information [5]. Regular inspections of the data logs must be recorded, where this explicitly listed requirement in CQI-9 [5] applies equally to computer data.

The aim of trend displays is to trace the important parameters of a process so that deviations can be recognized as early on as possible, and then suitable corrective measures taken before any defective products are produced.

It follows that the trend display also allows the calculation of derived process capability indicators (such as "process capability" of temperature regulation), and subsequently the statistical process control (SPC) of important process parameters. This way, the effects of a process change are discernible before they affect the product. The SPC can ensure that the natural variance within the production processes does not obscure any process changes that could result in a defective product [11].

Machine Data Acquisition (MDA)

Machine data acquisition is a means of monitoring performance. Machine data provide information on the utilization and efficiency of a system The simplest kind of machine data acquisition is operating hour meters and operating cycle counters, e.g. for counting the operating time of the heater or clock cycles [12].

Another kind of data transmitted and processed in automated thermal processing systems is order data. Order data can be transferred from the upstream ERP or PPS and progress reports returned to it. That way, the operators receive informative operating figures such as utilization, throughput, changeover times, availability and overall efficiency. From this information, organizational and technical weak points, such as bottlenecks in material flow, can be diagnosed more quickly.

Up to now, there are only very few companies that process machine data further in a maintenance context. And yet, without reference to machine data, in particular operating hours or cycles, preventative periodical maintenance is downright futile [12].

Preventative Maintenance

In order to guarantee the ability to deliver, the auto industry prescribes a system of preventative maintenance of manufacturing facilities as a general rule [5]. Strictly speaking, the maintenance strategy must take into consideration every single resource or every single functional group, or at least all process-relevant resources. This system, program or organizational approach should be systematic and comprehensible. The maintenance plan should include the maintenance intervals and scope of maintenance. Any faults or damage occurred in the past must also be accounted for [5].

Function-Related, Easy-Maintenance Layout

Not every functional group has the same operational wear as other groups. It hardly goes without saying, therefore, that a function-related, modular layout is needed. This applies both to the machinery and to the automation systems. A modular layout allows, for

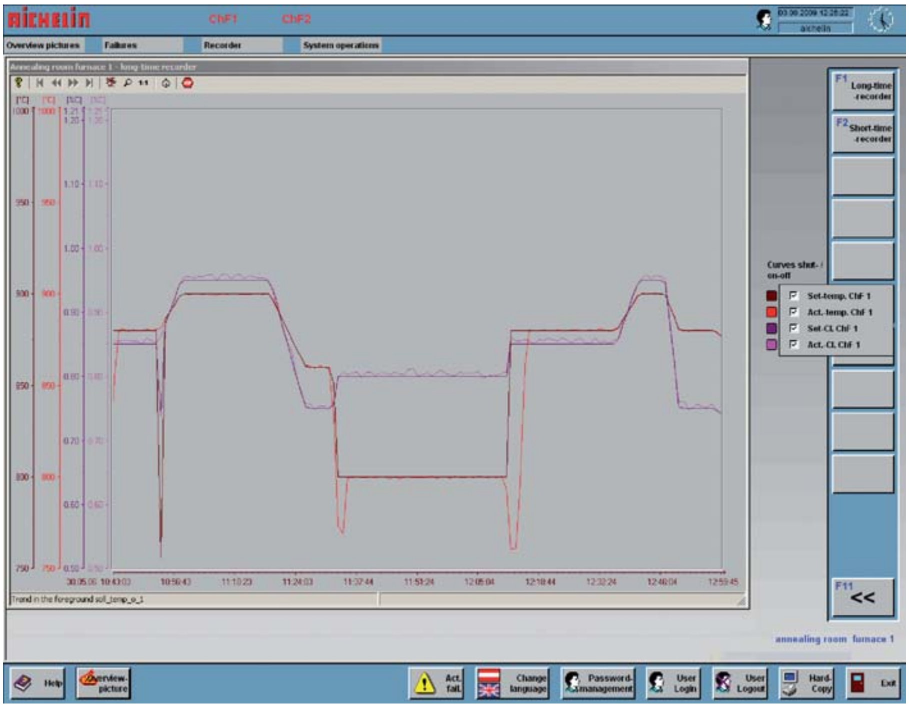


Fig. 6: Variables recording

example, the automation system resources in the switch cabinet to be structured according to functions. In the case of preventative maintenance, the resources in this function group can be easily located and changed [12].

Monitoring and Calibration of Thermocouples

Particular attention has to be paid to the preventative maintenance of sensors, such as thermocouples and C-level sensors [9].

The condition, calibration and functional reliability of thermocouples must be checked regularly [5]. If a comparative measurement is not performed automatically upon a temperature measurement (for verification), then a comparative measurement must be performed manually and recorded. A comparative measurement of installed measuring equipment involves determining the difference between the checked instrument and a calibrated instrument [8]. Important is that the observed difference must be within the prescribed tolerances. This ensures that all conceivable errors such as linearization, balance lines, reference junction temperature and, if necessary, drift are accounted for. If the measured value deviates, then the drift relating to the calibration measurement can be compensated using offsets.

Operating Manual

An operating manual for the thermal process must be present. The operating manual must be accessible to the heat treatment employees and must describe the entire heat treatment process, in particular the procedure to follow for potential emergencies [5]. It must be easy to search and find information in the manual.

It is therefore worthwhile to integrate the operating instructions into the electronic operating and monitoring system of the thermal processing system. Even the standard functions of most text programs allow comfortable navigation for searching and finding text segments in comprehensive manuals.

It should be pointed out here that CQI-9 regards an adequate description of the emergency strategies as an essential element of a quality management system.

Modernization of Existing Thermal Processing Systems

What has to be done if an existing thermal processing system does not satisfy the requirements of the automotive industry in one or more respects?

All companies that want to conserve the value of their thermal processing system will not get around having to modernize their automation at some stage. In principle, any old system can be upgraded to the level of a new, CQI-9-compliant system. It is merely a matter of the cost, and therefore the economy of the measure. This modernization revolves around migrating from SIMATIC S5 to SIMATIC S7 technology [14].

Aside from increasing availability and conserving the value of a thermal processing system, modernizing the control system brings many other technical and economic benefits with it. For example: access to a wider range of integrated automation functions, integration of the controller into networks, say, to transmit automatically production data from a production control computer, or integration of additional functions such as visualization and data archiving [14].

Examples for CQI-9-compliant modernization would be electronic lot tracing for product traceability, parts and recipe databases, easy controls and monitoring systems, quality assurance measures such as the Heat Treatment Certificate, or even performance increases by automating previously manual processes. Another popular reason for modernization is to introduce remote serviceability and advanced diagnostics options.

There are special conditions that must be considered when modernizing, however. Perhaps most important is to minimize downtimes during the conversion, since a thermal processing system is only one link in the entire chain of a capital and cost-intensive production plant. The planning and preparation of comprehensive CQI-9-compliant modernizations demands a high degree of precision and experience. Only that way complex modernizations will be accomplishable with only a few days of lost production.

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