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Intelligent heat treatment atmosphere optimisation and cloud-based advisor services

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While closed loop atmosphere control in carburising is state of the art, nitrogen-based atmospheres for carbon steel annealing, hardening and sintering furnaces are commonly operated with fixed flow rate settings. Without proper atmosphere control, these processes suffer from the risks of decarburisation or surface oxidation. The emerging trends in Industry 4.0 involving smart sensors, real-time process monitoring, and data analytics have allowed the development of an intelligent annealing furnace atmosphere advisor system for operating these heat treating processes in the desired thermodynamic condition. The atmosphere monitoring and control system also provides real-time alarms if deviations occur in the process and deliver valuable information about the atmosphere performance and utility supply. Operating parameters are collected through various sensors installed on the furnace, which are used for thermodynamic calculations of furnace atmosphere and for feedback about changes influencing the furnace conditions. This atmosphere monitoring and advising system adjusts the heat treatment atmosphere automatically based on optimised set-points for different products. As a result, atmosphere costs can also be optimised, with greater assurances on part quality and reduction of rejects. The advisor system can also provide guidance on furnace maintenance and utility supply. This paper provides an overview and case study of this heat treatment atmosphere advisor platform, which can be tailored to customer needs. It aims to provide the operator with enough information about the atmosphere conditions and trends, resulting in greater operational reliability and reduced costs.

The pressure on cost reduction and requirements on process documentation and reliability have increased the interest in data-driven optimisation of industry processes, ushering in significant changes in the heat treatment industry. The main goal and vision is to collect process information, analyse the information, add input and output variables from linked processes, complete the outcome with human knowledge or results from examinations and finally develop a smart system, which continuously monitors the relevant process and quality information in real time and adjusts the process accordingly [1].

In the heat treatment process of metal parts, tailored atmospheres are used to prevent undesired metal surface reactions and to adjust the desired mechanical properties of the parts. For steel parts, undesired reactions between the atmosphere and the parts could be surface oxidation as well as surface decarburisation, both caused by oxygen (O_2), water (H_2O) or carbon dioxide (CO_2) impurities. Furthermore, the surface condition and cleanliness after heat treatment depends on the furnace atmosphere composition and removal of oils or other residuals. Therefore, nitrogen (N_2) / hydrogen (H_2) based atmospheres are used in the heat treatment industry for metal annealing processes to produce a bright and clean surface finish. For avoiding decarburisation, an atmosphere blend of N_2, H_2 and propane (C_3H_8) is used in hardening and annealing applications. In carburising or hardening, Endogas atmosphere consisting of N_2, H_2 and carbon monoxide (CO) is commonly used.

While the control of Endo-generated atmospheres (N_2, H_2, CO blend) in carburising and hardening atmospheres is well-established and standard controllers are available from several suppliers, N_2/ H_2- or N_2/ C_3H_8 blends for annealing and hardening are still operated under uncertain atmosphere conditions. In nearly all annealing processes the atmosphere itself is not fully monitored or controlled. In hardening lines operated with a N_2/C_3H_8 blend, an

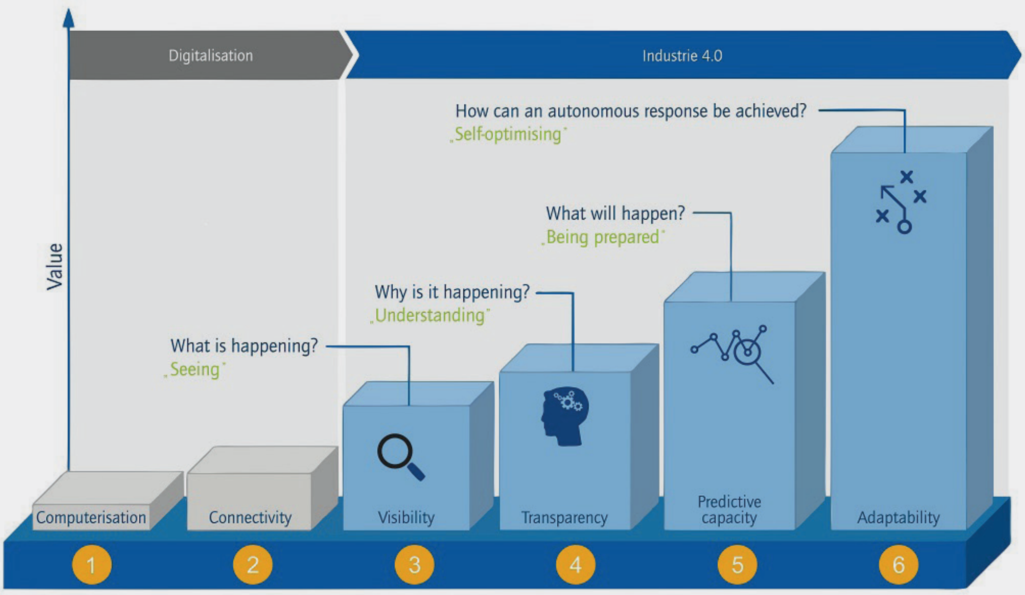

Fig. 1: Industry 4.0 development phases [1, 4]

oxygen probe is typically used, but this is not enough to avoid decarburisation. The atmospheres are usually introduced into the furnace with a pre-mixed blend ratio and flow rate. Typically, the gas composition and flow rates are designed for the worst-case scenario. In absence of active monitoring and control of the process, unexpected external influences like air ingress can contaminate the atmosphere, resulting in oxidation and decarburisation issues, leading to high costs due to rejects or rework. In some cases, pure N_2 atmosphere is also used for annealing of carbon steel parts to avoid the need for a hydrogen tank or endothermic generator on site. A N_2 atmosphere containing 10 ppm of oxidising components can still lead to a dull surface finish due to surface oxidation.

This paper describes the beginning of a cloud-based process advisor system for annealing and hardening processes of carbon steel and other metals, based on real-time monitoring and control of the atmosphere. For N_2-H_2 or N_2-C_xH_y atmospheres, the system can regulate the flow of H_2 and/or C_xH_y based on thermodynamic modelling with real-time furnace measurements. This allows further process optimisations like recipe development for different annealing applications or early identification of furnace or process issues. In addition, the system is capable of providing real-time alerts based on deviation from long-term historical data. It can be used for scheduling preventive maintenance and therefore allows the operator to control shutdowns and troubleshooting efforts. It was found in a customer case study, that the surface finish of the annealed products has been improved and rework as well as atmosphere costs were reduced. In cases where a pre-set N_2/H_2 blend is used, the system can help reduce overall atmosphere costs either by reducing the amount of H_2 used or by reducing the overall atmosphere consumption. In cases where a pure N_2/C_xH_y atmosphere is used, the system can help avoiding decarburising and thereby rejects.

BACKGROUND AND SYSTEM DESIGN

The intent of the project is to develop an intelligent retrofit system for existing annealing, hardening and sintering lines which helps the operators to combine the benefit of a closed loop control system on site with cloud based data collection and data analytics, including advise for the furnace operation and maintenance, in alignment with Industry 4.0 trends (**Fig. 1**).

The Air Products process advisor system has capabilities to control the atmosphere based on set-points for the oxidising potential and the dew point to avoid surface oxidation and decarburisation [2]. This system consists of:

- Data collection, making the process more visible
- Analytics and comparison of key indicators and furnace information over a longer term providing historic comparison between similar processes and indication why something happened (transparency)
- Forecasting products with quality variations based on real-time analytics and benchmark with historical data, advising the operator on the heat treatment issue.

Air Products has set up a cloud-based server infrastructure ("Air Products Process Intelligence System") to connect customer installations, track all available data and information and run customer specific algorithms to improve

Table 1: Relevant furnace data for the advisor system

Requirements for	Measure	Device	Reason
N_2 / H_2 atmospheres	Atmosphere temperature	Thermocouple	■ Calculate oxidising or carbon potential ■ Identify issues with heating or temperature profile
	O_2 atmosphere	Oxygen probe or sensor	■ Calculate dew point with H_2 or oxidising potential ■ Monitor oxidising potential and control furnace ■ Atmosphere against a set-point
	H_2 atmosphere	Thermal conductivity analyser	■ Calculate oxidising potential and dew point ■ Control dew point against a set-point to avoid decarburisation
	H_2 supplied blend	Thermal conductivity analyser	■ Identify furnace or supply issues
N_2 / H_2 / CO atmospheres	CO atmosphere	Infrared analyser	■ Calculate carbon potential ■ Monitor and control carbon potential against a set-point
Alternative or helpful operating parameter	CO_2 atmosphere	Infrared analyser	■ Calculate carbon potential (back-up to O_2 probe)
	DP atmosphere	Dew point analyser or zirconia-oxide probe	■ Calculate oxidising potential
	Furnace pressure	Pressure indicator	■ Monitor furnace tightness
	Atmosphere flow to furnace	Flow meter	■ Monitor sufficient atmosphere flow to avoid air ingress
	Atmosphere supply pressure	Pressure indicator	■ Identify gas supply issues
	Charge weight	Weight or manual input	■ Impact of charge weight on atmosphere compositions and part quality
	Charge surface	Manual input	■ Impact of part surface area on atmosphere compositions and part quality
	Part speed or annealing time	Motor or timer	■ Impact of heat treatment time on atmosphere compositions and part quality

the process. **Fig. 2** shows a schematic set-up of the overall system. All required atmosphere information for the closed loop atmosphere control system is connected to the atmosphere control system, which is installed on site and handles the thermodynamic calculations to monitor and control the furnace atmosphere.

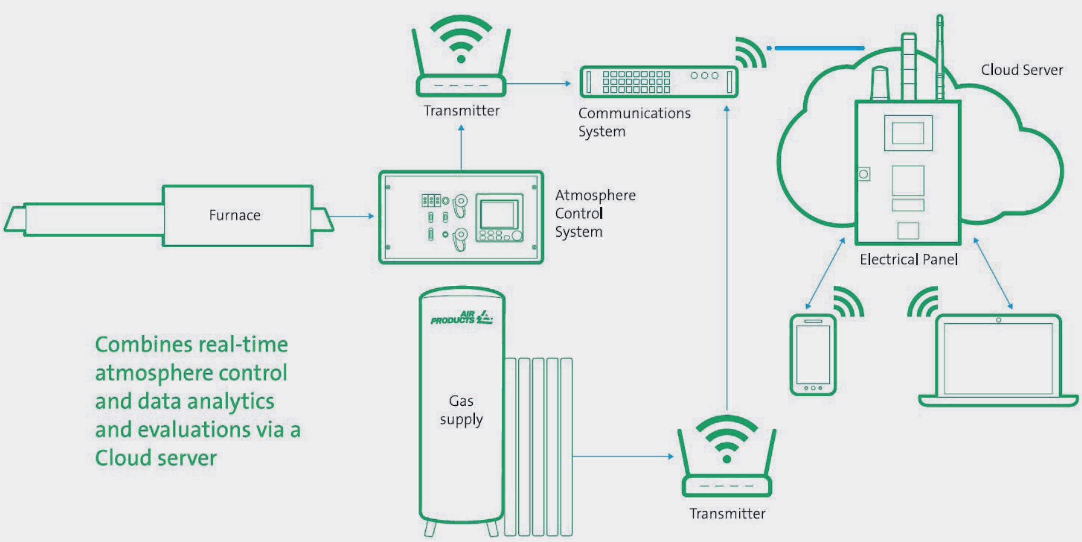

Fig. 2: Set-up of the cloud-based advisor system

Fig. 3: Electrical cloud panel

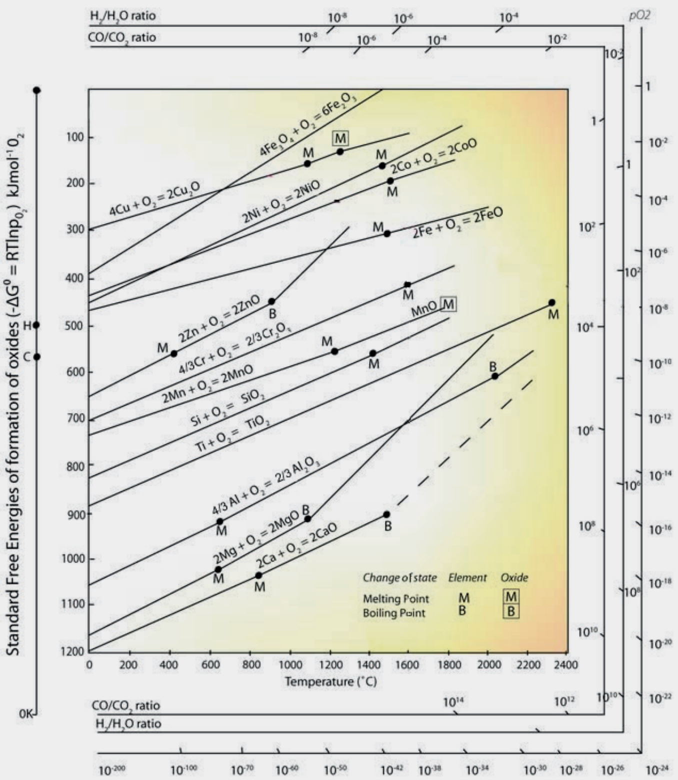

Fig. 4: Ellingham-Richardson diagram [3]

Additional information like atmosphere flow rates, atmosphere composition, supply pressure, etc. can be tracked directly by the cloud server. A list of examples for relevant furnace data is listed in **Table 1**.

Algorithms, which are not related to the furnace control system but would be helpful to identify furnace issues or improve the process can be monitored and analysed on the cloud server.

For transferring the data to the cloud server, an electrical panel is installed on site (**Fig. 3**), which is able to collect the data from the atmosphere control system but also all other, additional furnace data. This can be done via analog signals, digital inputs or wireless LAN nodes (Transmitter) for long distances. The separate set-up of the atmosphere control system and cloud server ensures proper operation of the furnace even when the communication of the network to the cloud server is interrupted for a certain time. During the interruption, the integrated datalogger of the electrical panel will record all data and transfer the data to the cloud once the network is established again.

INSTALLATION OF THE AIR PRODUCTS PROCESS ADVISOR SYSTEM

Considerations

When operating a roller hearth furnace for carbon steel parts several external influences and parameters need to be considered for choosing the right atmosphere, such as:

- Open or closed furnace
- Batch or continuous process
- Operating temperature
- Residual contaminations of the product surface
- Restrictions on the use of flammable atmospheres.

The annealing furnace in the case study [2] could be operated with a N_2/2 % H_2 atmosphere blend as a fixed setting for a bright surface finish, or with a pure N_2 atmosphere achieving a slightly dull surface finish. The goal here is to achieve a bright surface finish with limited H_2 addition, taking into consideration that some H_2 is created from cracking of oil contaminations during the heating phase. The set-up of the gas supply is a standard installation with a N_2 tank, H_2 packs and a standard N_2/H_2 blender to create a fixed blend to be fed to the furnace. To control the H_2 flow to the furnace but also to ensure that not flammable gas blend in the furnace is created, the blender was set to a maximum H_2 content of 2 % and a solenoid valve is installed to control the H_2 to the furnace, opening and closing based on the set-points of the atmosphere control system to adjust the right H_2O/H_2 ratio (=K) to avoid surface oxidation as shown in the literature (**Fig. 4**).

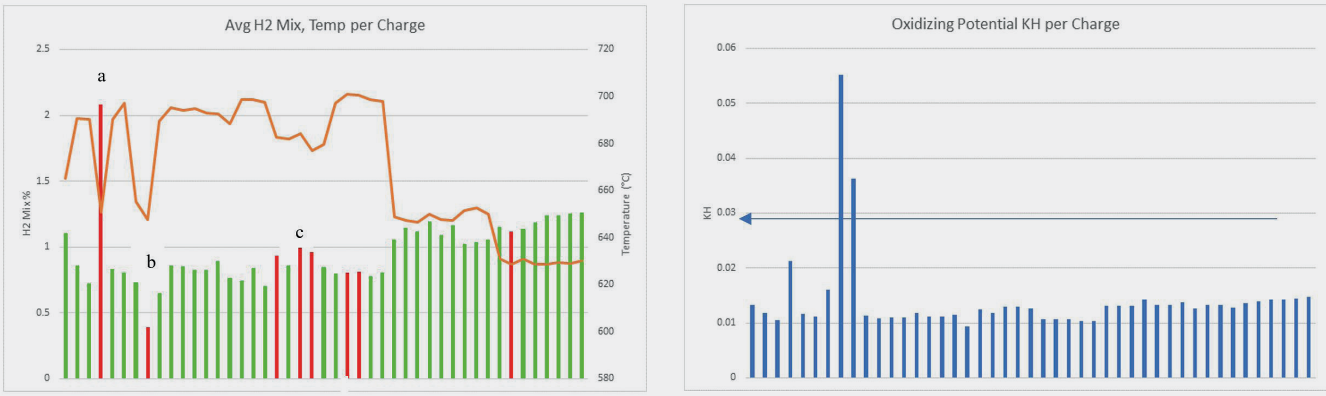

Fig. 5: Example of atmosphere compositions for several charges at different annealing temperature

Process optimisation

Annealing furnaces are typically not operated at the same temperature for all products. The temperature is adjusted to the different materials and desired mechanical properties. Therefore, it would be expected, that atmosphere requirements and atmosphere compositions are different for different annealing temperatures or materials. Furthermore, cracking and vaporisation characteristics of the impurities on the surface, like oil, can vary and the required H_2 content for a reducing atmosphere can vary as well, considering the same leakage rate and amount of impurities being carried into the furnace. Also, the surface area of the annealed product has an impact on the atmosphere composition.

Some of the influencing parameters of the ingoing product are currently unknown by the adviser system, the advisor system just monitors the information and provides an indication for variations. However, if the input information can be linked to a certain material and product and the operating window for "good" quality is defined, the advisor system can indicate when the process is going worse and if information about possible external influences are added to the system, it could determinate the reason.

Using the data collected with the Air Products process advisor system it is possible to calculate and compare the key performance parameters for the annealing process over a longer term. The atmosphere control system is controlling the atmosphere on a desired set-point for K and dew point to achieve the desired surface quality. For each individual charge the average KH (= H_2O/H_2 ratio) for the heating and annealing cycle can be calculated. However, related to the type of product and depending of operating parameters the length of the heating cycle and time to get the furnace conditioned is different and therefore reflected in the average KH-value being calculated over the overall heat treatment cycle.

With the historic trends for each annealing temperature band which is used, an historical average KHa can be defined for a sufficient part surface quality:

$$KHa = \frac{1}{n}\sum_{i=1}^{n} KHi$$

Along with the historical data for KHa, the annealing temperature, the atmosphere supply conditions, and other parameter as indicated in Table 1, operating limits can be defined for different annealing cycles and "good" surface quality. Furthermore, the average H_2 consumption used for the annealing process is a parameter reflecting the overall furnace condition. The required H_2 consumption should be lower for higher annealing temperatures and for a tight furnace and clean surface of the product. This means that just monitoring and comparing the oxidising potential K and the required H_2 feed to the furnace (H_2 mix) provides a first indication about the furnace and process conditions. As long as the parameters of the ongoing or last annealing cycle is within the operating limits, the operator gets a green indicator.

Tighter operating limits can be defined for some critical variables, providing early warning of a drift or variation (orange light). A red indicator highlights a larger variation that will possibly cause surface quality issues.

Fig. 5 shows such a visualisation of the charges in a customer's production process. Each bar reflects a charge which is annealed with a certain average H_2 consumption (green or red) at a certain temperature (orange line) with an average KH (blue bar).

In the example in Fig. 5, good quality is achieved with a KH of < 0.015 and an average H_2 mix into the furnace depending on annealing temperature between 0.7 and 1.3 %.

Table 2: Examples of troubleshooting advice

Charge	Observation	Expected result	Advice
a	Maximum H_2 consumption has been used, but K is above tolerable limit	Surface oxidation	Product with high oil contamination might have been treated – improve cleaning process for future charges
b	Used H_2 comsumption is very low, but KH is very high	Surface oxidation	H_2 supply issue
c	KH is below the tolerable limit	Clear surface	Higher H_2 consumption being used, possible reason: Oil contamination on the surface

As shown here, charges, which vary from this normal production, can be easily identified based on the measurement, calculations and deviation from historical trends.

Table 2 shows several examples of troubleshooting advice which the system can provide.

CONCLUSION

The Air Products process advisor system has been installed on a heat treatment furnace, combining real-time atmosphere control and data analytics and evaluations via a cloud server.

As a result of the implementation of the system, the following customer benefits have been demonstrated:

- The atmosphere costs have been reduced significantly (in the case study H_2 consumption was reduced by > 30 % [2])
- Rework of material with undesired, oxidised surface quality after heat treatment has been reduced
- Problems with the cleaning process of the input material into the heat treatment process can be identified in an early stage, reducing rejects and rework
- Furnace issues like slowly increasing leakages or leaks in burner radiant tubes can be identified early.

The development of the cloud-based process advisor system is in an early stage. With more information captured from processes, modelling accuracy and predictions can be improved, resulting in reduced failure rates and more cost-optimised operations.

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