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Heat Treatment Process Energy Efficient Design and Optimisation

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Abstract

Energy efficiency optimization ICT (Information and Communication Technology) solutions are currently being developed for energy saving in buildings and, to some ex-tent, also for the manufacturing domain. This paper describes an approach and ICT tool developed for manufacturing process energy efficiency optimization, in particular focused on the heat treatment process of steel casting parts. Traditionally this manufacturing process is designed based on experts experience selecting a predefined temperature-time curve provided customer specifications for the resulting steel parts. However this curve can actually be optimised in terms of energy consumption while keeping required mechanical properties. This improved design is what the tool here described provides, using knowledge based approach for process design and multivariate optimisation and simulation techniques for process optimisation.

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1. Introduction

The methodology and ICT components developed supporting manufacturing process energy efficiency optimisation described in this paper is focused on the heat treatment process of steel casting parts, and was

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implemented at *Fundiciones del Estanda* company located in Spain. The rationale behind this development was the understanding that the predefined temperature-time curves traditionally used for heat treatments can actually be optimized, given customer requirements, in terms of energy consumption and maintenance costs.

According to the new approach proposed, the process design starts with a preliminary process design based on experts' knowledge implemented in the tool, for example in terms of process 'design rules'. This preliminary process design is defined with intervals rather than specific values for each process parameter, and later on it undergoes optimisation in terms of energy and maintenance cost, then providing the optimal value for each process parameters within their respective intervals. A successful optimisation procedure requires the implementation of mathematical models relating process parameters to the resulting mechanical properties of the steel parts, as well as relating process parameters to energy and maintenance costs.

The following sections describe these steps followed in order to support the heat treatment optimisation, starting from the knowledge based preliminary process design, as well as the optimisation procedure and models implemented.

2. Heat treatment process energy consumption

The manufacturing process considered is the heat treatment of steel casting parts. This is actually a sub-process of the entire steel parts casting which includes sub-processes like melting, machining, grinding, cutting and cleaning and heat treatment. This heat treatment sub-process is powered by gas energy and accounts for over 33% of total gas consumed at the company, so it is reasonable to focus the energy efficient design on this specific sub-process. The main goal is to reduce the total energy consumption cost plus maintenance cost on the heat treatment process while at least keeping the resulting mechanical requirements in the steel parts.

A heat treatment process design starts with the selection of the suitable temperature-time curve for the part to be treated, which is defined based on personal experience of experts at the company. The process design basically consists of the definition of the Temperature-Time curve for the heat treatment for each type of part, given customer specifications (material and mechanical properties). Traditionally pre-defined Temperature-time curves are used, yet these curves can actually be optimised in terms of energy consumption. The DEMI tool developed supports the process designer for a quick preliminary process design based on implemented 'design rules' (knowledge based process design), and additionally includes a component supporting in the optimisation procedure. Heat treatment process, described by the T-t curve, usually consists of some few steps, which in its simplest way can be described as an initial heating, temperature holding time t, and a final cooling.

In addition to the energy consumption minimization, maintenance cost is also considered, so that the new process is profitable for the company. As long as mathematical correlations can be established between process parameters and energy and maintenance cost, the tool can provide support for process optimisation.

3. Methodology for process optimisation with DEMI tool

As above mentioned, heat treatment design basically means define the Temperature-Time curve for the steel parts given customer requirements. Predefined curves are normally used as starting point in process design, but these curves can actually be optimised in terms of energy consumption. The DEMI tool provides support in the process optimisation, and consists of several components, three of which are involved in this case:

- Energy Dependency Selector (EDS) providing a knowledge based preliminary manufacturing process design based on two techniques: Case Based Reasoning (CBR) and Rule Based Reasoning (RBR).

- Energy Analyser (EA) supporting optimisation of this preliminary process design, given ranges on process variables and constraints on requirements variables.

- Energy Simulator (ES) estimates the energy consumption of each possible specific process configuration provided by EA component, so that the minimum energy consumption process configuration can be finally selected.

Figure 1 shows the generic process design procedure based on DEMI tools (boxes in grey). All DEMI components communicate each other via web services and sharing information in a Knowledge Repository (KR). The connection between KR-EA-ES for configuration optimisation of another industrial case (compressed air systems) has been described in Friden et al (2012).

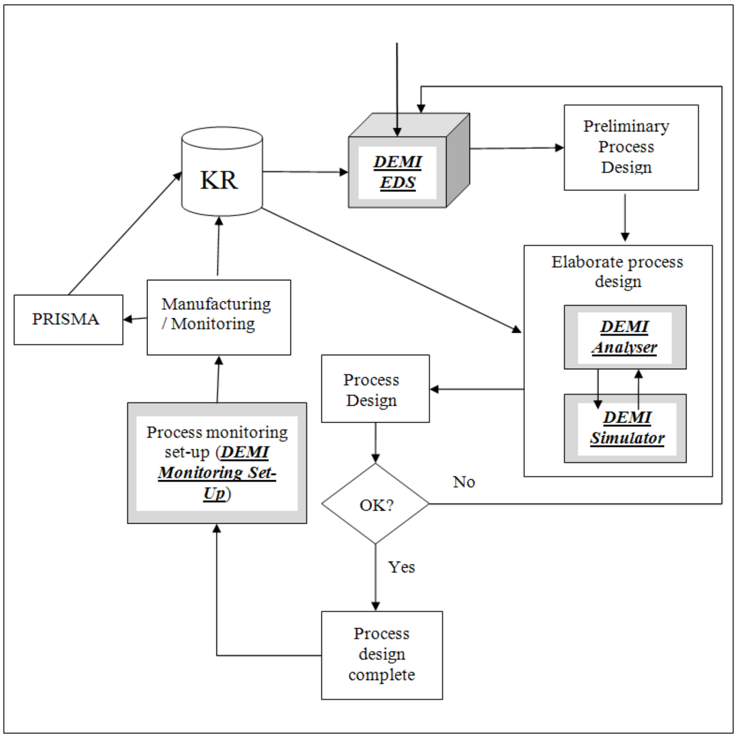

Fig. 1. DEMI components in manufacturing process design.

In order to optimise the heat treatment process design keeping the resulting steel parts' mechanical properties, some mathematical models have to be ready relating the different sets of parameters involved. If an analytical model considering the physics involved is not achievable due to the problem complexity, an empirical model approach should be followed, which would require a huge historic data-base allowing correlations among parameters be found. The different sets of parameters considered are the following:

- Heat treatment process parameters, including: Date/time, Material Load, Type of material and Heat treatment Temperature-time curve, for a simplified process defined by initial temperature, maximum temperature, time at maximum temperature and heating/cooling speed.

- Measured resulting mechanical properties of parts after heat treatment processes, currently stored in quality tests documentation at the company. Mechanical properties considered are the following: Yield and Ultimate strength, Strain, Resilience and Hardness.

- Maintenance cost parameters of historic processes, currently stored at *Fundiciones del Estanda* by PRISMA software database, provided by the company Sisteplant[1]. The main maintenance cost parameters considered are: Mean Time Between Failures (MTBF), Number of breakdowns (per year), Cost of breakdown (average working hours, material, idle time).

3.1. Knowledge based process design with EDS

A preliminary manufacturing process design can be quickly defined based on experts' experience, which can be described in terms of rules and successful historic processes. This knowledge based preliminary process design is done with the support of the DEMI component Energy Dependency Selector (EDS), allowing the process designer to quickly see the consequences of choosing different alternatives in the early stages of process design, also in terms of energy consumption. EDS component provides a preliminary process design based on two techniques: Case Based Reasoning (CBR) and Rule Based Reasoning (RBR).

Case Based Reasoning provides historic process designs 'similar' to the target process requirements given by the designer. In this case the requirements are those from the customer, basically material and mechanical properties required. This functionality requires historic cases database defined and populated including parameters describing the requirements, in addition to those describing the process design. The 'similarity' of historic processes with respect to required parameters values provided by the user is estimated according to the relative weights given for each parameter. The tool finally provides a list of historic processes sorted by similarity. This functionality implementation is based on the JColibri tool (Díaz-Agudo et al. 2007) and the process shown in Fig 2.

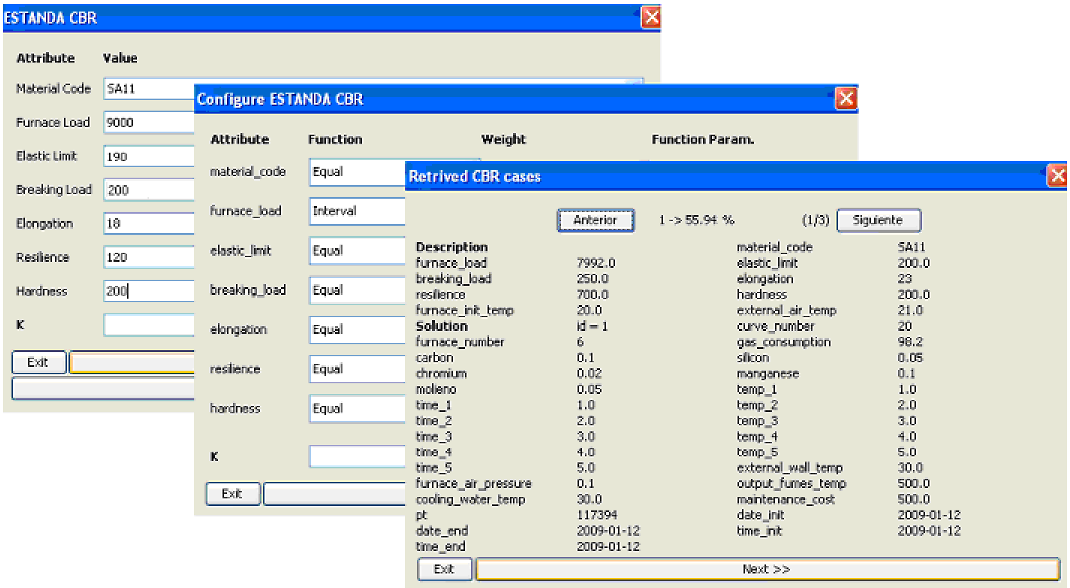

Fig. 2. CBR for case based heat treatment process design.

Rule Based Reasoning. This functionality provides preliminary process design based on experts' experience implemented in terms of 'rules'. The design sequence implemented with the rule based reasoning approach reproduces the way a process designer follows when designing a process: starting from process requirements the

[1] http://prisma.sisteplant.com

tool provides rule based feedback about the basic process design characteristics. This functionality is based on the tool KnowWE (Baumeister et al. 2007), for which several plug-ins have been developed in order to connect it to KR. A basic implementation is shown in Fig 3, where the user introduces Material and Constraints (mechanical properties required) and the tool provides process parameters intervals based on implemented rules, in this way defining a preliminary process design, matching user requirements, for optimisation.

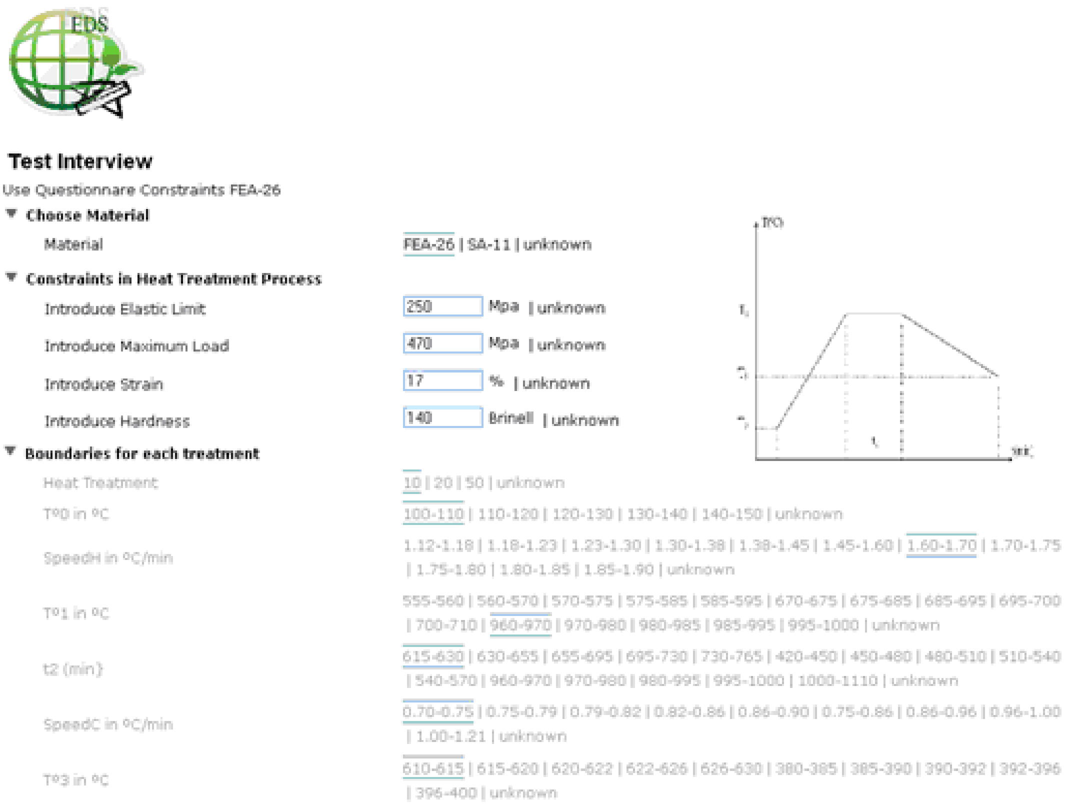

Fig. 3. RBR for rule based heat treatment process design.

3.2. Knowledge based process design with EDS

Optimisation process starts once the preliminary process design is given by EDS component. DEMI component Energy Analyser (EA) provides support in this optimisation procedure in terms of energy and maintenance cost, keeping required mechanical properties as constraints. EA searches for optimal process design, using in turn DEMI Energy Simulator (ES) for energy consumption estimation of each potentially optimal design configuration considered. Both DEMI EA and ES components main characteristics in heat treatment process design are briefly described below.

Process optimisation supported by EA

Once the preliminary heat treatment curve is provided by EDS, EA component searches for the optimised process configuration in terms of energy and maintenance cost, based on the implemented mathematical models relating process parameters, quality parameters and costs. EA looks for the minimum cost based on the existing models, given ranges on process variables and constraints on requirements variables. Process variables have to be within their given boundaries and constrained by requirements given by the user. So EA requires information related to the preliminary process definition (provided by EDS) and boundary limits for all the relevant parameters values.

The different sets of parameters above described have to be linked through mathematical models and expressed as objective function. It is important to remark that these models are intended to allow a comparison between different process designs performance, rather than accurate predictions on energy use, maintenance cost or mechanical properties, so that alternative process designs proposed by EA can be simulated by ES, compared by EA and finally an improved process design provided as result part of the optimisation procedure. The relations between sets of parameters and mathematical modelling approach considered are the following:

- Relationship between process design parameters and mechanical properties required. This model is based on experts' considerations about the influence of process parameters over the resulting mechanical properties. In this way a process optimisation can be performed while keeping constraints on mechanical properties.

- Relationship between process design parameters and maintenance cost. According to experts' criteria, the impact of process parameters modifications in maintenance cost can be estimated, and optimisation in terms of maintenance cost performed as long as these parameters correlations are accurate enough.

The EA procedure is basically as follows: EA Client calls EA with the process configuration ID; EA reads configuration ID with info about the nodes from the Knowledge Repository (KR), as well as initial data, boundaries for process variables, and constraints for quality variables from KR; EA starts Matlab, as a server, for process optimisation; For energy process optimisation, EA uses function *fmincon* to find minimum energy given ranges on process variables and constraints on quality variables; EA uses ES as a service to evaluate energy for each iterated process during optimisation, gets energy consumption estimations from ES and is able to predict quality variables (mechanical properties) for each configuration; EA finally sends to KR the process parameters values describing the optimal process design.

Process energy consumption simulation with ES

Energy Simulator (ES) estimates the energy consumption of each possible specific process configuration provided by EA component, so that the minimum energy consumption process configuration can be finally selected. In general, ES is a tool intended for simulation of network system or process, when energy consumption is of interest. ES is constructed as a simulation service able to simulate new/innovative network or system designs and estimate energy use for them. The analytical modelling and simulation is based on "block-based modelling" concept rather than on purely "process-based modelling". It means that whole physical process is decomposed into sub-processes represented by independent blocks (one block for one sub-process). Sub-process is process variable (output of block) related to physical behaviour of other variables (inputs of block) with their weighting coefficients (block parameters). Sub-process may be expressed as a process variable or function dependent on other process variables, as described in Iešmantas and Alzbutas (2012).

ES requires a theoretical model for energy use estimation provided a process con-figuration. In the case of heat treatment process at the company a basic thermodynamic model has been considered. This model expresses gas consumption and energy balance of the heat treatment process, taking into consideration the following energy terms: Energy provided by the gas, Energy lost by fumes, Heat stored by parts after treatment, Heat stored by furnace refractory, Heat losses through the furnace walls.

This theoretical model is the basis of ES component, also running in Matlab, which receives a given process design from EA. The data needed for this energy consumption estimation are the following, given by the process parameters values describing the process: Material type (specific heat) of the treated parts, Parts load (mass) to be treated, Difference between parts final and initial temperature, Total process time, Configuration of heat treatment process. Energy balance of such a process can be simplified considering only the main terms as follows:

- Energy provided by the gas, depending on gas consumption (time dependent) and gas calorific power. Total gas consumption is the parameter to be estimated.

- Energy lost by fumes, depending on fumes mass and enthalpy.

- Heat stored by parts after treatment, depending on the parts load, steel specific heat and temperature net increment of the parts.

- Heat stored by furnace refractory, depending on the furnace refractory mass, its specific heat and temperature net increment.

- Heat losses through the furnace walls, depending on energy loss per unit time (time dependent), furnace walls area and process duration.

In order to structure the workflow of power consumption estimation, ES employs four main functionalities: Get configuration (after unique ID from EA is received, ES will connect via web services to the KR and retrieve information about the process configuration), Add blocks (identifies different phases of heat treatment process), Specify connections (creates the heating model from specific phases identified in the previous functionality), Calculate energy use of process configuration (performs estimation of used gas volume together with consumed power).

4. Conclusions

The set of tools here described supports in the optimisation of heat treatment process in terms of energy efficiency and maintenance costs while keeping the required mechanical properties. In addition, tools supporting knowledge based decision making as those in EDS component allow the company to keep and reuse the experts' knowledge and experience for a quick preliminary process design, while EA and ES components support the process design optimisation. These components can work in a distributed way with a common Knowledge Repository based on web services. On the other hand, this set of tools can be adapted to other manufacturing processes where correlations between process parameters and resulting quality parameters can be established, as well as a model for energy use estimation, so this approach is portable to other manufacturing processes and companies.

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