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Steel nitriding optimization through multi-objective and FEM analysis ☆

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Abstract

Steel nitriding is a thermo-chemical process leading to surface hardening and improvement in fatigue properties. The process is strongly influenced by many different variables such as steel composition, nitrogen potential, temperature, time, and quenching media. In the present study, the influence of such parameters affecting physic-chemical and mechanical properties of nitride steels was evaluated. The aim was to streamline the process by numerical–experimental analysis allowing defining the optimal conditions for the success of the process. Input parameters–output results correlations were calculated through the employment of a multi-objective optimization software, modeFRONTIER (Esteco). The mechanical and microstructural results belonging to the nitriding process, performed with different processing conditions for various steels, are presented. The data were employed to obtain the analytical equations describing nitriding behavior as a function of nitriding parameters and steel composition. The obtained model was validated, through control designs, and optimized by taking into account physical and processing conditions.

Keywords: Nitriding; Mechanical properties; Optimization

1. Introduction

The deep analysis of industrial processes necessitates the employment of computational multiobjective optimization tools. Optimization instruments allow integration with multiple calculation tools and post-processing tools. modeFRONTIER platform allows the organization of a wide range of software and an easy management of the entire product development process. The role of the optimization algorithm is to identify the solutions which lie on the trade-off curve, known as the Pareto Frontier. These solutions have the characteristic that none of the objectives can be improved without prejudicing another. Here, Design of Experiment (DoE) technique is used to perform a reduced number of calculations. After that, these well-distributed results can be used to create an interpolating surface. This surface represents a meta-model of the original problem and can be used to perform the optimization without computing any further analyses.

Once data has been obtained, the user can turn to the extensive post-processing features in modeFRONTIER to analyze the results.

Not so many papers are available in literature on the analysis on thermo-mechanical diffusion processes of nitriding based on Fick's laws model. In the present paper the behavior of nitriding process, performed on different steels (40 different materials) in a broad range of processing parameters (600 experimental conditions), is analyzed. The study leads to the description of the nitriding effect on the steel structures and mechanical properties. In [1] the authors give a mathematical description to predict the nitrogen contents as well as residual stresses and distortions after nitride quenching. The model was implemented in finite element calculations in order to identify the concentration profiles. They concluded that the interactions between diffusion of nitrogen also need to be established. In general, the hardening of steels during nitriding process is due to the N-based compounds precipitation [2]. The precipitation sequence is also strongly influenced by the compounds time formation. Several nitrogen mass transfer mechanisms have been proposed to describe the nitrides precipitation process. In [3], the authors analyzed the nitriding process by employing the Mullins–Sekerka equations on the interface separating a growing nitride layer in pure iron. They showed that a plane interface is unconditionally stable due to the favorable

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Nomenclature

T_H	heat treatment temperature
N_p	nitrogen potential
T_N	nitriding temperature
t_N	nitriding time
N_*xxx*	nitrogen concentration at *xxx* μm from the surface
ε_s	distance from the surface of the starting point of ε phase
ε_f	distance from the surface of the ending point of ε phase
γ'_s	distance from the surface of the starting point of γ' phase
γ'_f	distance from the surface of the ending point of γ' phase
Hv_*xxx*	microhardness at *xxx* μm from the surface
σ_*xxx*	residual stresses at *xxx* μm from the surface

combination of the Gibbs–Thomson effect, and of the concentration fields. This result is specific to the nitriding configuration where the net flux of nitrogen is in the growth direction. The influence of compositional and misfit generated stresses on the morphological stability has been discussed qualitatively. For these reasons, in the present paper, a large attention vas devoted to the measurement and the control of compound layers and on their effect on mechanical properties. Other authors described results of simulations of diffusional process of nitrogen on pure iron. They underline the effect of nitriding potential of NH_3–H_2 atmosphere on microstructural constitution and growth kinetics of nitride layers. They demonstrate that both microstructural nature and thicknesses of nitrided layers as well as the nitrogen profile within the formed phases during gas nitriding can be predicted [4,5]. In [6], a generalized Wagner diffusion model was used to analyze the layer formation and growth in definite experiments on plasma nitriding of pure iron. The model is able to predict the compound layer composition. It can be used as a method for calculation of the effective diffusion coefficients in the first sublayer of the compound zone. The thickness of the compound layer and the diffusion zone as well as their phase composition and the consequent mechanical properties depends on the nitriding temperature and time. It also depends on the nitrogen activity of the medium in which the nitriding process is taking place. In addition such chemical–physical processes depend on the state of the material before nitriding [7]. For this reason, in the present multi-objective optimization analysis the state of the material (in particular the heat treatment temperature) before nitriding was taken into account. In [8] the authors modeled the nitrogen decomposition on the steel surface as a consequence of processing parameters. In [9] the authors evidence the nitride layers formation in high temperature gas nitriding of stainless steel. In [10,11] other authors underline the nitriding properties of steel after treatment at high temperatures up to 1050 °C. In [12] the authors model the process through finite element analyses by employing microstructural data obtained from X-rays diffraction measurements. The same methods for microstructural evolution monitoring are described in [13]. The method is largely

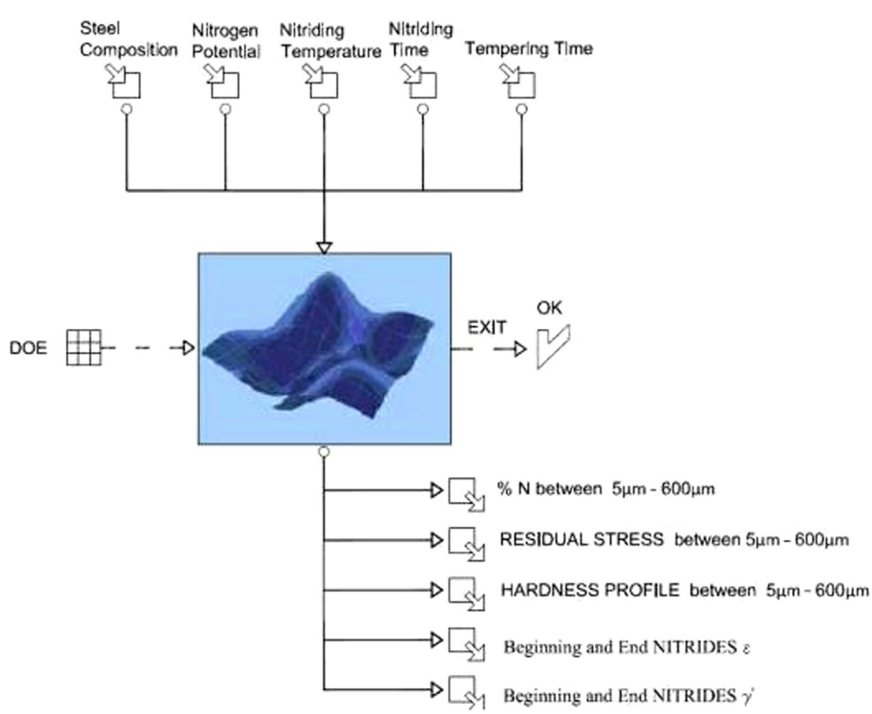

Fig. 1. Workflow of analysis describing the input–output correlation.