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XFEM investigation of a crack path in residual stresses resulting from quenching ☆

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ABSTRACT

The aim of this work is the numerical study of a crack path in a residual stress field resulting from a manufacturing process such as quenching. An XFEM technique is proposed to that end and the example illustrating the quenching of a large thick plate is considered so as to demonstrate the capability of the method proposed. Indeed, during the quenching of steels, metallurgical transformations can occur, leading to high residual stresses at room temperature. From the practical point of view, the thick plate must be sawn after quenching. But it is experimentally observed that, under certain quenching conditions, the crack initiated by the sawing, suddenly propagates through the thickness of the plate and then rotates through an angle of about 90°. The numerical simulation of quenching is detailed and the results obtained under two operating conditions are given. Then the XFEM technique applied to the crack propagation in a residual stress field is presented and the cracking path obtained on the quenched plate is compared to that obtained using the FEM coupled with a remeshing technique. It is shown that the computed crack path justifies experimental observations.

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1. Introduction

The quenching process is often used in industry to improve the material properties of many mechanical steel components. The quenching of steels involves a fast cooling stage from an austenitic state generally obtained in a furnace. Due to the concomitant gradients of thermal strain and to the volume changes associated with the transformation of austenite into bainite or martensite during the cooling, residual stresses and distorsions occur in the component during the process. The residual stress state can be responsible for quench cracks. But the component can also be sawn after quenching and the propagation path of the crack initiated by the sawing strongly depends on the residual stress field, which can lead to surprising cutting profiles.

Measuring residual stresses through the thickness of a thick component so as to study the propagation path of a possible crack is utterly impossible. The numerical simulation of the quenching process is therefore the only way to access the residual stress field but the interactions between heat transfer, metallurgical transformations and stress–strain, as summarized in Fig. 1, have to be accurately taken into account. A large number of research studies have been carried out for simulating the temperature field, the metallurgical changes and the stresses and distorsions induced by quenching. One can cite the work of Inoue and Raniecki [1], Denis et al. [2], Bergheau et al. [3] and more recently Kang et al. [4] and Li et al. [5] propose finite element programs to investigate the process parameters, Carlone et al. [6] focus on the prediction of the metallurgical structure, Da Silva et al. [7] study the distorsions of a C-ring and Lingamanaik and Chen [8] include the effects of carburizing. The finite element method is generally used [3] for the numerical simulations.

Studies concerning the propagation of a possible defect in the residual stress fields created by a quenching process are much rarer. Autesserre [9,10] proposed to use the finite element method combined with a remeshing technique and a second order fracture criterion to simulate the propagation of a crack in a quenched thick plate. But this type of approach is time consuming and is relatively complicated to implement. Moreover, when the piece is subjected to an initial (residual) stress field, this method raises the problem of the internal variables projection from one mesh to another. The past years have seen the emergence of new techniques to take account of the geometry of a crack and its evolution during propagation. The most popular enriched technique is the eXtended finite element method introduced by Moes et al. [11] for crack growth. It is based on the partition of the unity property of finite elements identified by Melenk and Babuska [12]. This approach is closely related to the GFEM technique proposed by Strouboulis et al. [13,14]. The XFEM method avoids both

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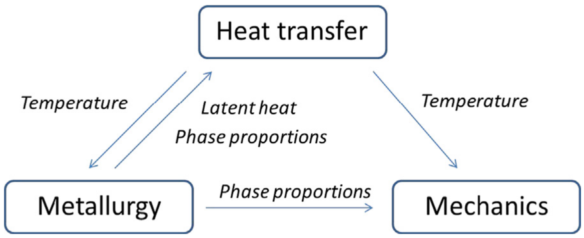

Fig. 1. Couplings between heat transfer, metallurgy and mechanics.

remeshing and the difficulty of the projection of internal variables such as phase proportions and plastic strains which are at the origin of the residual stress field in our case study. Therefore, the XFEM method is quite easy to use. Recently, Gallina [15] used the XFEM method to predict the formation of cracks during quenching but, to our knowledge, the simulation of a crack path in a component after quenching using XFEM has never been investigated.

In this paper we propose to study the mechanical effects of water quenching on a large thick plate made of 40CMD8 steel, the dimensions of which are 0.4*3*5 m. This example comes from a real case study which has been studied by Autesserre [9]. After being completely austenitized in a furnace, the plate is quenched in water and then cooled in air up to room temperature before being sawn. Experience has shown that reducing the quenching time in water can lead to adverse effects, the sawing step becoming impossible to realize. It turns out that the saw initiates a crack which propagates almost instantly without following the desired trajectory because it rotates through an angle of about 90°. To understand the origin of this phenomenon by means of numerical modeling, this paper proposes a finite element approach to simulate the quenching step, followed by an XFEM simulation to compute the crack's propagation.

Section 2 presents the numerical simulation of the quenching of steel components. All the phenomena and their interactions which need to be taken into account to compute residual stresses are detailed. Section 3 presents the case study and the computed results for different quenching conditions. Section 4 focuses on the modeling of crack propagation in a residual stress field and especially the analysis of the crack initiated by the saw in the case of interrupted quenching conditions. A comparison of the crack paths obtained with FEM coupled with a remeshing technique is presented to show the interest of the numerical approach proposed.

2. Simulation of quenching

2.1. Heat transfer

Considering the Fourier conduction law, the heat equation writes:

$$\begin{cases} \rho \dot{H} = \mathrm{div}(\lambda \ \mathrm{grad}\ T) & \text{in } \Omega \\ \lambda \ \mathrm{grad}\ T \cdot \mathbf{n} = h(T^{(p)} - T) & \text{on } \partial\Omega \end{cases} \tag{1}$$

where ρ is the material volumetric mass, H is the specific enthalpy, T is the temperature, λ is the thermal conductivity, $T^{(p)}$ is the temperature of the quench liquid and $\mathbf{n}$ is the unit outward normal vector to the boundary $\partial\Omega$ of the domain Ω representing the volume of the work piece. h is a coefficient which represents the heat exchanged between the mechanical component and the quench fluid supposed to be at the temperature $T^{(p)}$ during the cooling phase [16]. These two parameters can depend on space and time and may be determined or adjusted, for example, from measurements of the drasticity.

The weak formulation of the heat equation is classically obtained by multiplying Eq. $(1)_1$ by weighing function T^* and integrating over the domain Ω [17]. Integrating by parts and accounting for the boundary condition $(1)_2$, one thus obtains the following weak formulation:

$$\int_\Omega \mathrm{grad}\ T^* \lambda \ \mathrm{grad}\ T\ dv + \int_\Omega T^* \rho \dot{H}\ dv = \int_{\partial\Omega} T^* h (T^{(p)} - T)\ ds \tag{2}$$

Following the usual procedure, the weak formulation (2) is applied to the finite element approximation of the function T given by

$$T \approx \sum_{i=1}^{N} N_i T_i \tag{3}$$

In this expression, N denotes the number of nodes, T_i the value of the function T at node i and N_i the shape function associated to this node. Following Galerkin's approach, the weighting function T^* takes the same form.

Applying for instance an implicit Euler algorithm for time discretization of the enthalpy H [18], the finite element method then leads to solve at each time step a system of N equations of the form:

$$\int_\Omega \mathrm{grad}(N_i) \lambda \ \mathrm{grad}(T)\ dv + \int_\Omega N_i \rho \frac{\Delta H}{\Delta t} dv - \int_{\partial\Omega} N_i h \left(T^{(p)} - T\right) ds = 0 \tag{4}$$

2.2. Metallurgical transformations and thermo-metallurgical couplings

Three types of interaction between thermal and metallurgical phenomena must be considered [19,3]:

- metallurgical transformations depend on the thermal history,
- metallurgical transformations are accompanied by latent heat effects which modify temperature distributions,
- thermal properties are phase dependent.

Different approaches can be used to describe the transformation kinetics in steels [20–22]. These approaches rest upon the modeling of transformations under either isothermal conditions (IT diagrams) or anisothermal conditions. In the latter case, parameters come from CCT diagrams. The model we use in this study lies in the second category. Generally, those models can be expressed, in the case of one transformation, with a differential equation of the following type:

$$\dot{p} = f(p, T, \ldots) \tag{5}$$

where p is the proportion of the created phase. Leblond and Devaux [21] have suggested the use of a simple first order differential equation of the form:

$$\dot{p} = \frac{\overline{p}(T) - p}{\tau(T)} F\left(\dot{T}\right) \tag{6}$$

$\overline{p}(T)$ denotes the phase proportion obtained after an infinite time at temperature T, $\tau(T)$ a time delay depending on temperature T and $F(\dot{T})$ a function representing the dependency of the transformation rate with the temperature rate. These parameters are adjusted for each transformation in order to represent the CCT diagram. One can note that if the $F(\dot{T})$ is chosen proportional to $\dot{T}$, then the resulting phase proportion only depends on temperature as is the case for martensitic transformation which follows the Koistinen–Marburger law [23]:

$$p(T) = (1 - e^{-b(M_s - T)}) \tag{7}$$

where M_s and b respectively characterize the temperature at the beginning of transformation and the evolution of transformation with temperature. In such a case, one has to choose $\overline{p}(T) = 1$ for $T \le M_s$ and 0 else and $\tau = 1/b$. The effect of stresses on

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