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Multiparameter Optimization of Mechanical Cutting Process of Grain Oriented Silicon Steel

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In this paper, the applications of a mesh-free smoothed particle hydrodynamics methodology for simulating and analysing the 3D slitting process is presented. The developed model is used to analyse the residual stresses and deformation in grain-oriented electrical steels during and after the process under different conditions. The experimental research included both assessing the quality of the cut edge of the material and an analysis of its selected magnetic properties. Obtained results are used in multiparameter optimization process with delivered scripts in Matlab program. A set of acceptable solutions is developed on the plane of controllable variables (of technological parameters) on account of accepted criteria (operational indicators) and limitations. Using obtained relationships, functions, and results, it is possible to control cutting process and obtain high cut surface quality and minimum deterioration of magnetic properties.

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1. Introduction

The most important parameters that characterize the magnetic sheets are total losses, magnetization, residual induction, eddy current, hysteresis loss, magnetic permeability, coercivity, magnetostriction, and anisotropy. The process of production determines all of these parameters with chemical composition. Grain-oriented electrical steel sheets after the production process are exposed to the deterioration of the magnetic properties in the subsequent processing steps of core production. A cutting processes for example: guillotining, blanking, punching, or shear-slitting are usually used for the mechanical separation of materials [1, 2]. They allow for separating the sheet material at a low cost but also induce stresses and deformations in electrical steels and consequently the magnetic properties are partially deteriorated. According to many researchers, the reason for the deterioration of the magnetic properties is the change in the distribution of the flux density and hysteresis field [3–5]. Another problem with shearing processes is the deterioration of the cut surface's quality by the formation of burrs [3, 6]. The burr makes packetizing difficult. Analysing the state of stresses and strain in the sheet after shearing using experimental methods is very problematic. The analysis is usually determined by invasive methods (e.g. by drilling a series of small openings through which measuring winding is wound), which increases the error margin and, in many cases, is impossible when thin sheet areas are analysed. There are no well established known non-invasive methods of appointment because of some difficulties [7].

Shear-slitting is the most versatile and commonly used method to slit magnetic materials [1, 4, 5]. The main challenge for shear-slitting electrical steels is to obtain high quality products characterized by optimally sheared edge condition, minimum surface damage, freedom from burrs, slivers, edge wave, distortion, and residual stresses [8, 9]. The amount of adjustable process parameters and the fact that the influence of these parameters on the process of cutting grain-oriented electrical steels is not fully understood make it difficult to control the slitting process. Therefore, the final product frequently has serious defects and drawbacks, such as large deformation and defects on the sheared edge that increases the magnetic losses. The present paper shows new approach of analysis of magnetic sheets cutting process. This paper focuses on the numerical and experimental analysis of effect of slitting parameters on quality of sheared edge and magnetic properties based on grain oriented electrical steels. Using obtained relationships, functions, and results, the possibility to control cutting process and obtain high cut surface quality and minimum deterioration of magnetic properties are demonstrated.

2. Modeling of shear-slitting process

A three-dimensional finite element model of slitting is developed in the general-purpose finite element software package LS-DYNA and is presented in Fig. 1. The description of the nonlinearity of the material is conducted

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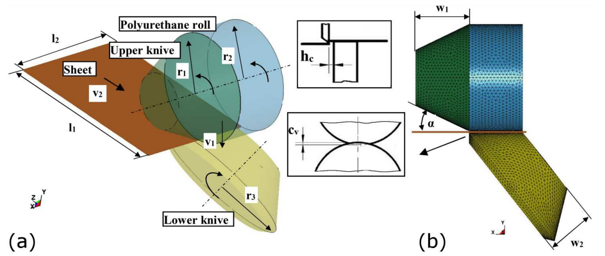

Fig. 1. (a) Coupled SPH-FE simulation model of shear slitting process (general view), (b) front view: c_v — vertical clearance, h_c — horizontal clearance, α — rake angle of the upper knife, r_1–r_3 — radius tools, l_1 — sheet length, l_2 — sheet width, w_1 and w_2 — tools width.

TABLE I

Mechanical and physical properties of the ET 122-30 steel.

Density [kg/dm^3]	Silicon content [%]	Yield point [MPa]	Tensile strength [MPa]	Elongation [%]	Hardness [HV$_5$]
7.65	3.1	300	370	11	160

using an incremental model that takes into account the influence of the history of strains and strain velocities. For the purpose of constructing the material model, the following is used: Huber–Mises–Hencky's nonlinear plasticity condition, the associated flow law and combined strengthening (i.e. isotropic and kinematic). The state of the material after the aforementioned processing is taken into account by introducing the following initial states: displacement, stresses, strains, and strain rate. The incremental contact model covers the contact forces, the contact rigidity, the contact boundary conditions, and the friction coefficients in this area. The mathematical model is supplemented with incremental equations of the object's motion and the uniqueness conditions. In order to reduce the calculation time, the cutting tools are modelled using finite element method (FEM), while the cut sheet is modelled using smoothed particle hydrodynamics (SPH) method.

The major difficulties during FEM modelling of cutting processes are resulted from the use of grid/mesh, which can lead to various problems in dealing with free surface, moving interface, deformable boundary, and crack propagation [6]. Mentioned disadvantages of the finite element models can be reduced using mesh-free methods, for example, smoothed particle hydrodynamics (SPH), which is implemented on the sheet model in order to accurately, simulate the material cracking mechanisms. ET 122-30 (0.3 mm thick) grain-oriented steel, which is often employed in the industry, is used to simulate the typical production conditions. The mechanical and physical properties of material are given in Table I.

3. Results of analysis

Numerical and experimental researches are carried out for the following constant technological process parameters: $c_v = 0.1$ mm, $\alpha = 30°$, $r_1 = 15$ mm, $r_2 = 15$ mm, $r_3 = 20$ mm, $w_1 = w_2 = 15$ mm, $l = 80$ mm, $w_i = 40$ mm, and different values of the cutting speed v_2 and horizontal clearance h_c. During the shear-slitting process, a high-speed camera, *i*-SPEED TR, together with a computer can record a set of consecutive images of the sample surface. For the analysis of shearing mechanisms, damage affected zone formation at workpiece, and validation of SPH model, a digital image correlation (DIC) technique is used. Developed model is used to analysis of width of deformation affected zone (damage zone), states of stresses, and deformations of material (Fig. 2).

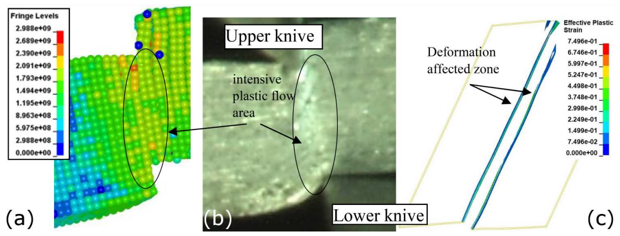

Fig. 2. Examples of numerical and experimental results of the cutting process: (a) elastoplastic phase SPH-FE simulation (view of crack front), (b) elastoplastic phase experiment (view of crack front), and (c) final workpiece (SPH-FE simulation).

The values of burr height are measured from the specimens at different locations over the cut edge using optical microscopy "Vision Engineering". An increase in the burr height indicates increasing the plastic deformation and may cause short circuits between single laminations, which implicate increasing eddy current losses. Magnetic property tests are made using samples of the shape of rings. This shape allowed them to be properly mounted in the magnetizing generator with an even distribution of tensile stresses in the material, and a closed magnetic path was obtained. The basic element of the stand was an automatic system for testing soft magnetic materials HB-PL1.0, which is used to measure the magnetic characteristics of steel. The influence of analyzed process parameters on the shape of magnetic hysteresis loop of the material are presented in Fig. 3. There can be observed changes in the hysteresis loop shapes related to the cutting speed settings, especially in the areas of the upper bending of the characteristic and saturation (Fig. 3a). Smaller changes occur when the clearance between cutting tools is changed in analyzed range and is most visible in the saturation areas (Fig. 3b).

4. Optimization of the process for industrial applications

The purpose of the task is to determine the optimal parameters of the transformer sheet cutting process. Production of transformers is very complicated, and if improperly carried out, it can result in a significant decrease

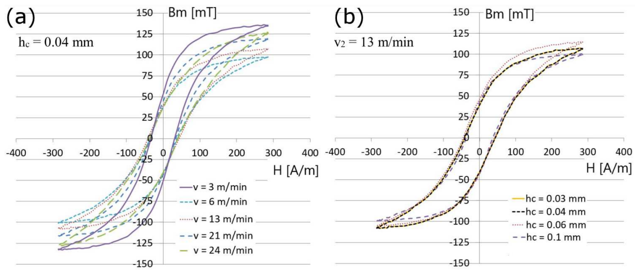

Fig. 3. Influence of the cutting speed and horizontal clearance on the magnetic characteristics $B(H)$ for the amplitude of the magnetic field intensity $H_m = 285$ A/m.

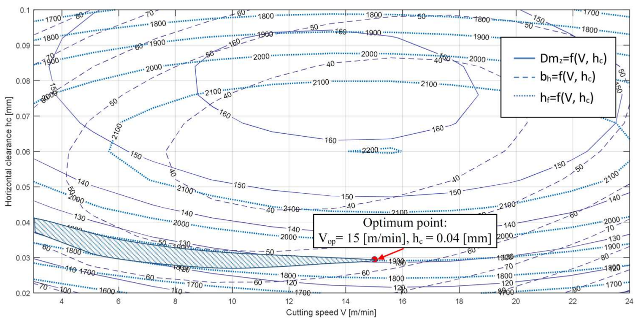

Fig. 4. Graphical optimization of the cutting process.

of the efficiency of ready devices. It was found that the size of the magnetic hysteresis field depends, among others, on the cutting method. It is known that the field contained inside the magnetic hysteresis loop represents energy losses associated with domain reorientation. From the point of view of the profitability of production, losses described in the area of the hysteresis loop area are allowed, however, high cutting efficiency is required.

Therefore, the optimization task is formulated as follows: hysteresis loop surface area should be not greater than $h_f \leq 1900$ mT A/m, width of the damage zone Dm_z should be smaller than 130 μm, and burr height (b_h) should be smaller than 60 μm. Performed restrictions allow for obtaining good quality product in terms of operation (high efficiency), however the problem is to determine the cutting process parameters to obtain the highest process efficiency, which results from the cutting speed v_1 and the clearance h_c used. In order to solve such a task, graphical optimization is done using Matlab software, which can be used as a heuristic optimization (Fig. 4). Mathematical models of Dm_z, b_h, and h_f changes in the function of v and h_c are obtained on the basis of the regression function type II using the theory of experiment planning and statistical development of results.

5. Conclusions

Proper selection of the technological parameters of mechanical cutting process of magnetic materials causes many problems on the production lines. It is a result of process nonlinearity (geometrical, physical, and thermal), large deformations, strain rate, friction and nonlinear material characteristics, and necessity of maintenance of magnetic properties. The paper presents new approach to analyse of this process using coupled numerical FEM-SPH and optimization methods. Using graphical optimization is very useful from the technical point of view, because it allows reading the technological parameters of the mechanical cutting process for the analyzed quality of the workpiece, e.g., damage zone width, burr height, and hysteresis field. For such a task, an area of acceptable solutions are developed, however, due to the efficiency of the cutting process, the following technological parameters are the most advantageous: $v_{op} = 15$ m/min, $h_c = 0.029$ mm.

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