Robotics and Computer Integrated Manufacturing xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Full length Article

Dull punch line is not a joke – Worn cutting edge causes higher iron losses in electrical steel piercing

Sampsa V.A. Laakso[a,*], Arijussi Väänänen[b], Sven Bossuyt[a], Antero Arkkio[c]

[a] Department of Mechanical Engineering, Aalto University, Espoo, 02150, Finland
[b] Department of Materials Science and Engineering, Aalto University, Espoo, 02150, Finland
[c] Department of Electrical Engineering and Automation, Aalto University, Espoo, 02150, Finland

ARTICLE INFO

Keywords:
Piercing
Electrical steel
Iron losses
FEM
Simulation
M400-50A

ABSTRACT

Electrical steel is used for the active parts in electrical machinery that form the magnetic circuits because the material experiences low iron loss, and thus, has superior magnetizing properties. A typical electrical sheet has a thickness of 0.5 mm and is punched into its final shape via a piercing process. Piercing causes large deformations and residual stresses in the narrow zone of the cut surface. The deformations and stresses weaken the magnetic properties of the electrical sheet and result in additional losses, as the iron loss increases after piercing [1]. This paper presents a simulation model of the piercing process to evaluate the deformations and stresses on the cut surface. The model is constructed using the commercial FEM solver Deform. There has been an attempt to simulate the magneto-mechanical state of the punched surfaces, but the piercing process itself was not simulated [2]. The electrical steel sheet investigated in this paper is isotropic electrical silicon steel M400-50A (EN 10106-96).

1. Introduction

Non-oriented electrical steels, such as M400-50A, are commonly used in rotating machines. The M400-50A designation reads as M for magnetising steel with maximum iron losses of 4 W/kg (400), 50 for a thickness of 0.5 mm and A for non-oriented grains. The iron losses in electrical steels can be divided into two main categories: hysteresis losses and dynamic losses. Dynamic losses can be further divided into classical losses and excess losses, which are significantly smaller than dynamic losses [3]. Piercing is a typical process for manufacturing electrical steel sheet parts. It results in good production output, relatively low production costs and consistent quality. However, the mechanical cutting of the sheet increases the iron losses in electrical steel, and therefore, it is important to minimise the deformations caused by the tool, especially since the standards set by the International Electrotechnical Commission (IEC) will have stricter limits regarding the energy efficiency of electromechanical machines in the near future, with an IE5 class efficiency that experts estimate will exceed the previous IE4 class (IEC 60034-30-1:2014) requirements by 20% [4,5]. To address this issue, simulation model of the piercing process is developed to investigate the effect of different tool and process parameters on the mechanical state of the cut surface. FEM simulations of blanking allows to predict edge quality, tool wear and forces, and the effect of the process parameters, but the quantitative accuracy of the simulations is strongly dependent on the modelling accuracy of the geometry and tool properties, such as the misalignment of the tool or tool deflections [1,6]. Simulations can be used to predict the iron losses instead of experimental work. One experimental procedure to identify the iron losses in the cutting edge region is presented by Holopainen et al. [7], where FeSi 3.2 alloy is characterized. The cutting edge deformation increased the iron losses by 38% [7]. Ossart et al. [2] developed a magneto-mechanistic model to describe the effect of plastic strain on the magnetic field and induction, both of which correlate quite well with the measured data [2]. Using the material data presented in [7], Rasilo et al. [8] simulated the iron losses in induction motor core laminations with the model proposed in [2]. The results were in good agreement with measured data and the total electromagnetic losses increased by 11.7% to 29.6% [8]. These results encouraged the authors of this paper to pursue full simulation chain from manufacturing process to ready assembled electrical motor. This paper addresses the first part of that simulation chain. Parts of the work presented in this paper has been previously published and presented in FAIM2016 conference and this paper is an extended version of that [9].

2. Materials and methods

A material model for M400-50A steel is required to simulate the piercing process. The Johnson–Cook material model [10] was selected

---

[*] Corresponding author.
E-mail address: sampsa.laakso@aalto.fi (S.V.A. Laakso).

https://doi.org/10.1016/j.rcim.2018.03.006
Received 27 February 2017; Received in revised form 3 April 2017; Accepted 13 March 2018
0736-5845/

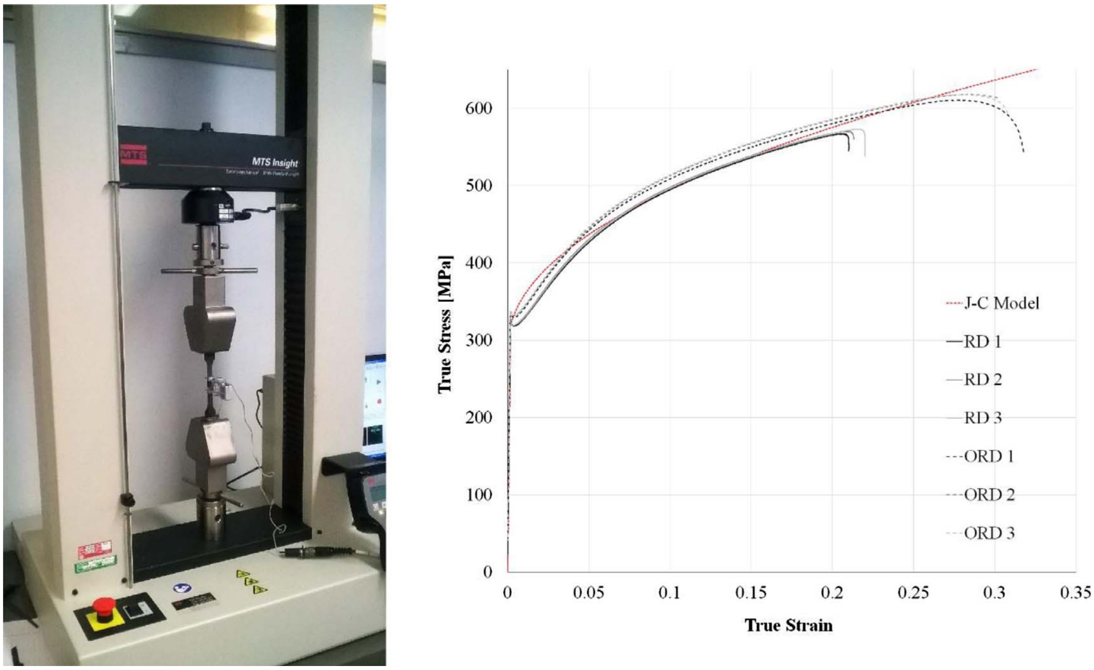

Fig. 1. Tensile testing equipment and test results in the rolling direction (RD) and orthogonal to rolling direction (ORD).

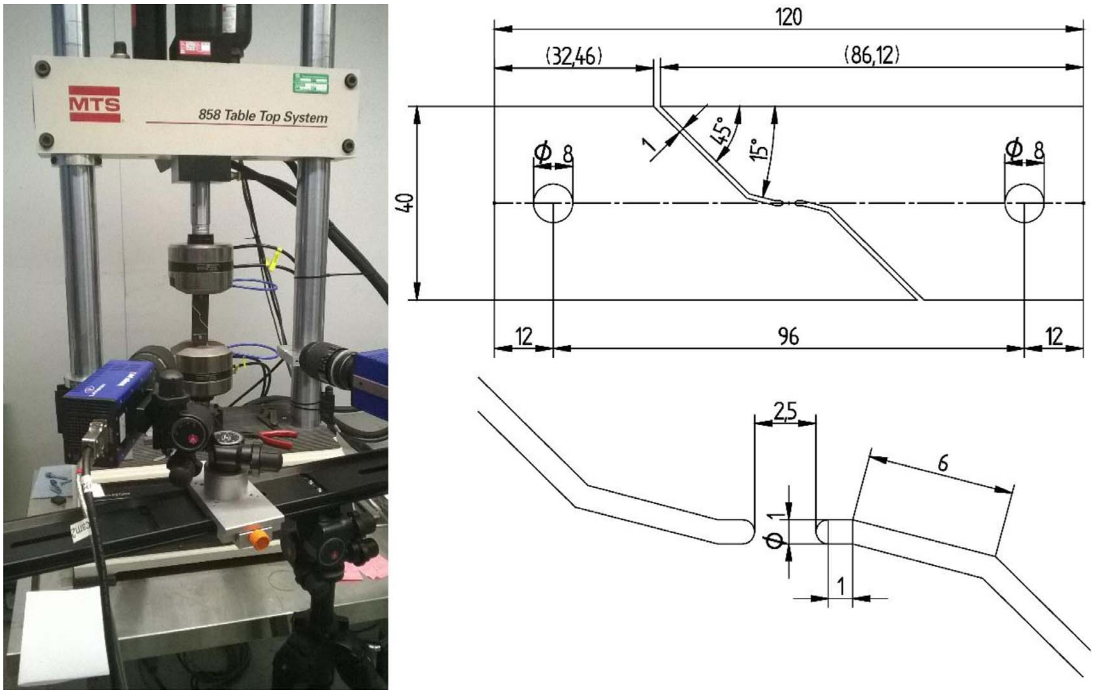

Fig. 2. MTS 858 tensile testing equipment setup with the LaVision DIC cameras for shear strain measurement and shear test specimen modified after recommendations by Tarigopula et al. [13].

for strain hardening and thermal softening instead of Hollomon model [11], that was used in the initial simulations. Cockcroft–Latham damage model [12] was selected for this study because both Johnson–-Cook and Cockcroft–Latham models are commonly used and not overly complex. Rate sensitivity is not considered in this study because it is assumed that its effect is negligible in the piercing process, but small values are given for the rate sensitivity parameters to improve convergence during the simulation.

$$\text{Johnson}-\text{Cook model:}\ \sigma = (A + B\varepsilon^{n})\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^{m}\right]$$

where A is yield equivalent, B *is* strain hardening multiplier, n is strain hardening exponent, m is thermal softening exponent, ε is strain, $\dot{\varepsilon}$ is strain rate T is temperature, T_{ref} is reference temperature, T_{melt} is melting temperature.