

# Calculating Iron Losses Taking into Account Effects of Manufacturing Processes

P. Goes<sup>\*1</sup>, E.Hoferlin<sup>1</sup> and M. De Wulf<sup>1</sup>

<sup>1</sup>OCAS N.V. – ArcelorMittal Research Gent

\*Corresponding author: John Kennedylaan 3 B9060 Zelzate, Belgium, Patrick.goes@arcelormittal.com

**Abstract:** Finite element modelling of electrical machines usually assumes uniform magnetic properties and loss behaviour throughout the steel laminations. It is well known that manufacturing processes, like the assembly of the machine, deteriorate the properties of the core material. Generally, the measured iron losses in the machine are higher than the losses obtained under standard conditions, the ratio being the so-called “building factor”. Taking advantage of the multiphysics capabilities offered by Comsol Multiphysics, a model was developed with magnetic properties and losses being dependent on the mechanical stresses introduced during assembly of the machine.

**Keywords:** iron losses, electrical machines, nonlinear material properties.

## 1. Introduction

These days, energy saving is the holy grail of engineering. Electrical machines transform mechanical energy into electrical energy or vice versa. Ferromagnetic materials are essential for concentrating the magnetic flux into the areas where it must generate forces. Electrical steels are developed to optimize their properties for use in laminated cores of electrical machines.

The ideal electrical steel has:

- High permeability: high B with low H, i.e. low currents and low copper losses.
- High saturation polarization, for the same reasons.
- Low electrical conductivity, for lower eddy currents in the core.

Additional non-electromagnetical properties, such as stampability, are required.

Manufacturing constraints make this ideal unattainable: trade-offs have to be made. Large efforts are being made in ArcelorMittal Research Gent to develop optimal electrical steel grades for specific applications. To assist customers in the selection and application of the ArcelorMittal electrical steels, finite element modelling studies are conducted as well.

## 2. Energy losses in electrical steels

### 2.1. Total loss $P_{tot}$

The methods for determining the loss properties are standardized. To measure core loss the material is mounted in an Epstein frame with a primary and a secondary winding around a test sample. An alternating current  $i(t)$  is generated in the primary winding, and the resultant secondary voltage  $v(t)$  is measured. The total energy loss per cycle is then obtained by integrating  $v(t) i(t)$  over one period  $T$  of the alternating current:

$$P_{tot} = \frac{1}{T} \int_0^T v(t) i(t) dt$$

It can be shown that this is equal to the area inside the BH-curve, which has units of tesla-amperes per meter, which is identical to joule per cubic meter, or the total loss per volume unit.

### 2.2. Hysteresis loss $P_{hyst}$

The hysteresis loss is the energy needed to make the material run through a magnetization cycle, when all induced eddy currents in the material, caused by the dynamics of the exciting field, are restricted to an absolute minimum. The corresponding loss per cycle is thus independent of the frequency  $f$ . The loss per time unit can be expressed as:

$$P_{hyst} = K_h B_{max}^2 f$$

### 2.3. Dynamic loss $P_{dyn}$

The dynamic loss is the difference of  $P_{tot}$  and  $P_{hyst}$ . This can be further separated into the classical Foucault loss (‘eddy current loss’) and excess loss. The equation for classical Foucault loss is:

$$P_c = \pi^2 \sigma d^2 (B_{max} f)^2 / 6$$

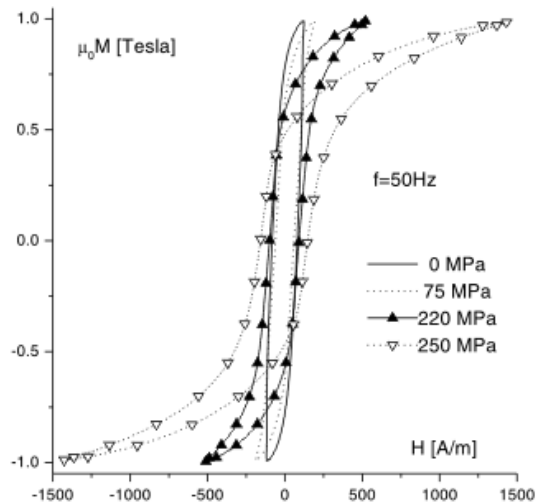
With  $\sigma$  the electrical conductivity and  $d$  the lamination thickness

### 3. Effect of mechanical stresses on the magnetic properties

The dependence of magnetic properties on mechanical stress during elastic and plastic deformation can be evaluated by means of special constructed equipment, ([Permiakov 2002]) consisting of a single sheet tester in which unidirectional tensile and compressive loads can be applied to the specimen.

#### 3.1. Effect on the magnetization loop

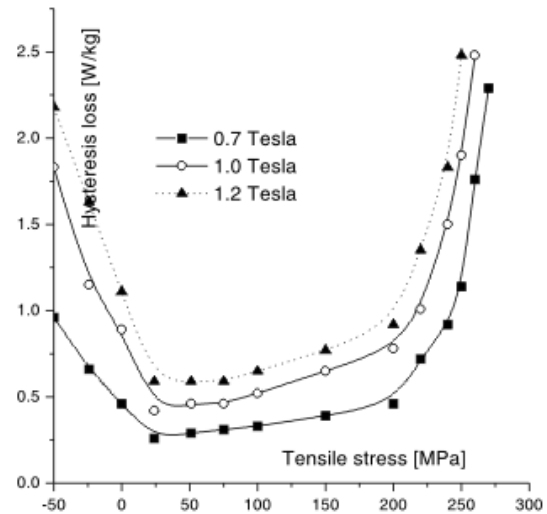
In general, the shape of the magnetization loops is changing during the application of stress, see Figure 1. The coercive field is increasing while the remanent induction and the permeability are decreasing.



**Figure 1.** Variation of magnetization loops under mechanical stress.

#### Effect on the hysteresis losses

Figure 2 depicts the hysteresis losses as a function of the tensile stress for the magnetization levels of 0.7, 1.0 and 1.2 Tesla and 50Hz sinusoidal magnetic flux.



**Figure 2.** Variation of hysteresis loss as a function of mechanical stress.

### 4. Application in the modelling of electrical machines

The stator of electrical machines is often assembled with the housing by means of press- or interference fitting. The housing inner diameter is slightly smaller than the stator's outer diameter. The housing can then be mounted by heating it, sliding it over the stator, and allowing it to cool. The shrinking housing compresses the stator core, and, as mentioned in the preceding paragraph, these mechanical stresses deteriorate the magnetic properties of the electrical steel.

We developed a model in Comsol multiphysics to quantify these effects.

### 5. Solving for the interference fitting stresses

The stresses occurring in the stator were calculated using the *plane strain (smpn) application mode* of the structural mechanics module, by including a thermal expansion load on the housing's subdomain and letting it cool down from a reference strain temperature down to the ambient strain temperature.

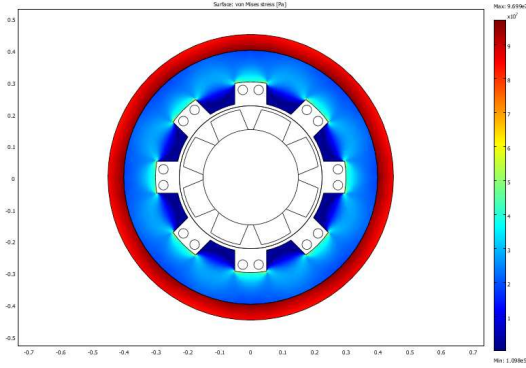


Figure 3. von mises stress field

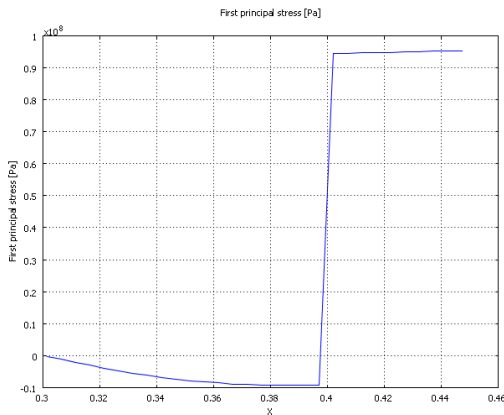


Figure 4. von mises stress along a radius

The line plot shows compressive stresses inside the stator and tensile stresses in the housing, as expected.

This stress state is subsequently used to modify the magnetic properties of the stator material.

## 6. Modelling the magnetic properties

For simulation purposes, the magnetization curve of electrical steel can be expressed as a function of just two parameters: the saturation polarization  $J_s$  and the relative permeability  $\mu_r$ :

$$B(H) = \mu_0 H + \frac{2 J_s}{\pi} \arctg \frac{\pi (\mu_r - 1) \mu_0 H}{2 J_s}$$

The effect of the stress can be introduced by a correction factor:

$$B(H, S) = B(H, 0) (1 + K_S B S)$$

With the factor  $K_S = 0.0035$  determined by fitting to experimental data, stresses being expressed in MPa.

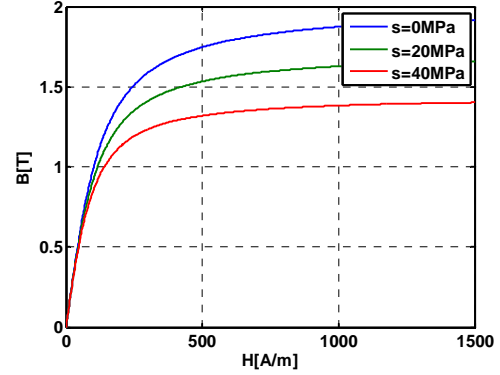
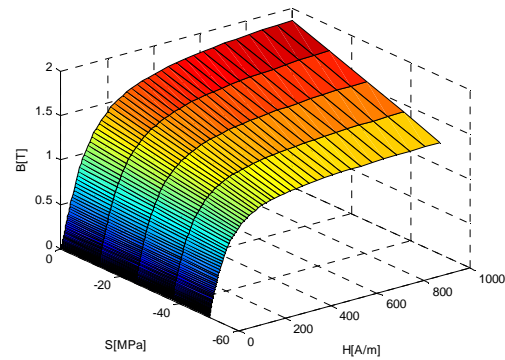
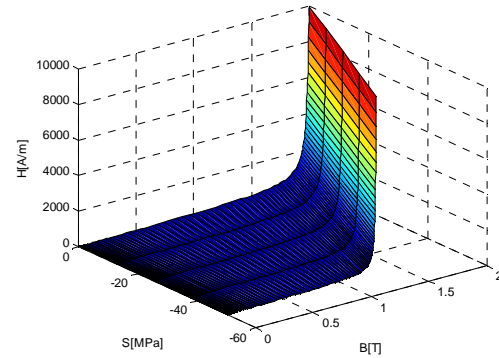


Figure 4. B-H curve as function of stress



As the *emqa* equation system needs  $H$  as a function of  $B$ , the above function has to be inverted.



This  $H(B, S)$  function is implemented in the Comsol model as a 2D interpolated table-lookup function.

## 7. Solving for the magnetic flux density

2D models of electrical machines are well suited for the *perpendicular induction currents, vector potential (emqa) application mode*: the currents are perpendicular to the modelling plane. This

implies that the magnetic field is present only in the modelling plane. Hence the magnetic vector potential has only one nonzero component, perpendicular to the modelling plane. Maxwell's equations simplify to a second-order scalar PDE with this magnetic potential component  $A_z$  as dependent variable.

The constitutive relation to be used is  $\mathbf{H} = f(|\mathbf{B}|) \cdot \mathbf{e}_B$ , with  $\mathbf{e}_B$  the unit vector pointing in the direction of the  $\mathbf{B}$ -field.

The AC/DC module's application mode supports nonlinear relationships between  $\mathbf{H}$  and  $\mathbf{B}$ .

Here however, we need  $\mathbf{H} = f(|\mathbf{B}|, S) \cdot \mathbf{e}_B$ , and this requires some modification of the equation system:

By default, the expressions for  $H_x$  and  $H_y$  refer to the HB interpolation function of the chosen material, e.g. `mat1_HB`:

```
if(normB_emqa==0, nojac(pdifff(mat1_HB(normB_emqa[1/T]))[A/m], normB_emqa)) * Bx_emqa, mat1_HB(normB_emqa[1/T])[A/m] * Bx_emqa / normB_emqa)
```

These expressions have to be modified in order to refer to the 2D interpolation function that describes the  $H = f(B, S)$ , e.g. `myHB2D`:

```
if(normB_emqa==0, nojac(pdifff(myHB2D(normB_emqa[1/T], mises_smpn[1/Pa]))[A/m], normB_emqa)) * Bx_emqa, myHB2D(normB_emqa[1/T], mises_smpn[1/Pa])[A/m] * Bx_emqa / normB_emqa)
```

By first solving the `smpn`-physics for the stress and subsequently solving `emqa`, one finds the  $\mathbf{B}$ -field degraded by the effects of the mechanical stresses.

## 8. Postprocessing for the losses

It is then a very simple matter to define the above expressions for the loss components as subdomain expressions, to generate loss maps, and to integrate over complete cycles of the machine to determine the overall core loss.

## 9. Electrical steels material library

A material library was developed, containing the ArcelorMittal electrical steels properties.

**10. Table 1: variables defined for electrical steels**

| variable | Font                | Description                      |
|----------|---------------------|----------------------------------|
| Js       | 2.1 [T]             | Saturation magnetic polarization |
| mur0     | 8000                | Relative permeability at $H=0$   |
| Kh       | 420 [W*s*T^-3*m^-3] | Hysteresis loss coefficient      |
| Ke       | 0.96                | Excess loss coefficient          |
| d        | 0.2[mm]             | Lamination thickness             |
| sigma    | 3.2e6[S/m]          | Electric conductivity            |

## 11. Conclusions

Performing these calculations using typical electromagnetic FEA products requires splitting the geometry into discrete affected and non-affected zones and assigning different material properties to each zone. As shown here, Comsol allows for continuous adaptation of the magnetic material properties, based on previous geometric and/or structural mechanical results.

## 12. References

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