Elektrodynamic Induction and Coupling to Thermodynamics und Structural Mechanics

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Summary:

For a structural analyst working with Finite Elements (FE), a number of important questions arise, when facing electrodynamic effects:

1. Which heat flux is induced by electric current?
2. Which forces are induced by electric and magnetic fields and acting on the structure?
3. Where can I get these quantities from and how can I apply them to my structure?

One obvious solution is to extend the structural model by electrodynamic contents. Then, all electrodynamic, thermodynamic, and mechanical calculations can be made with one single model. Induced heat and induced forces can be used for further calculations directly from this approach without any expensive mapping of the results between different software packages.

Of course, this solution requires that the same element types can be used for different types of analysis. That is the crucial point, because electromagnetic fields are permeating the entire space and the structure has to be used in all types of analysis. When structures are modified, the effect of this modification is automatically taken into account in all analyses.

Modeling and analysis are demonstrated by an industrial example. This example shows the analysis process of inductive hardening of a bolt, where an alternating magnetic field induces heat in the bolt. The resulting temperature increase in the structure is stopped by quenching. Beside the phase transition, which is the main effect of hardening, also elastic-plastic material effects occur in the bolt.

The analysis is performed by the industrial FE software PERMAS.

Keywords:

Electrodynamics, thermodynamic, structural analysis, inductive hardening, skin effect, elastic-plastic analysis

1 Introduction

Inductive hardening consists of the following steps:

1. An alternating current is applied to a coil of copper.
2. The current causes an alternating magnetic field around the coil.
3. This field induces an alternating current in the steel bolt.
4. The current heats up the surface of the bolt. The goal is to reach more than 900°C.
5. At high temperature, a phase transition to Austenite takes place in the bolt.
6. By quenching, this phase is preserved and results in a harder steel.
7. In addition, elastic-plastic effects in the bolt change the material properties in the bolt.

Fig. 1 shows the dimensional specification of a hardening scenario in 2D together with a 3D FE model. The 3D effect is due to the coil, which is not modeled in an axisymmetric way. Axisymmetric models have many advantages, but here the focus is to demonstrate the possibility of 3D models.

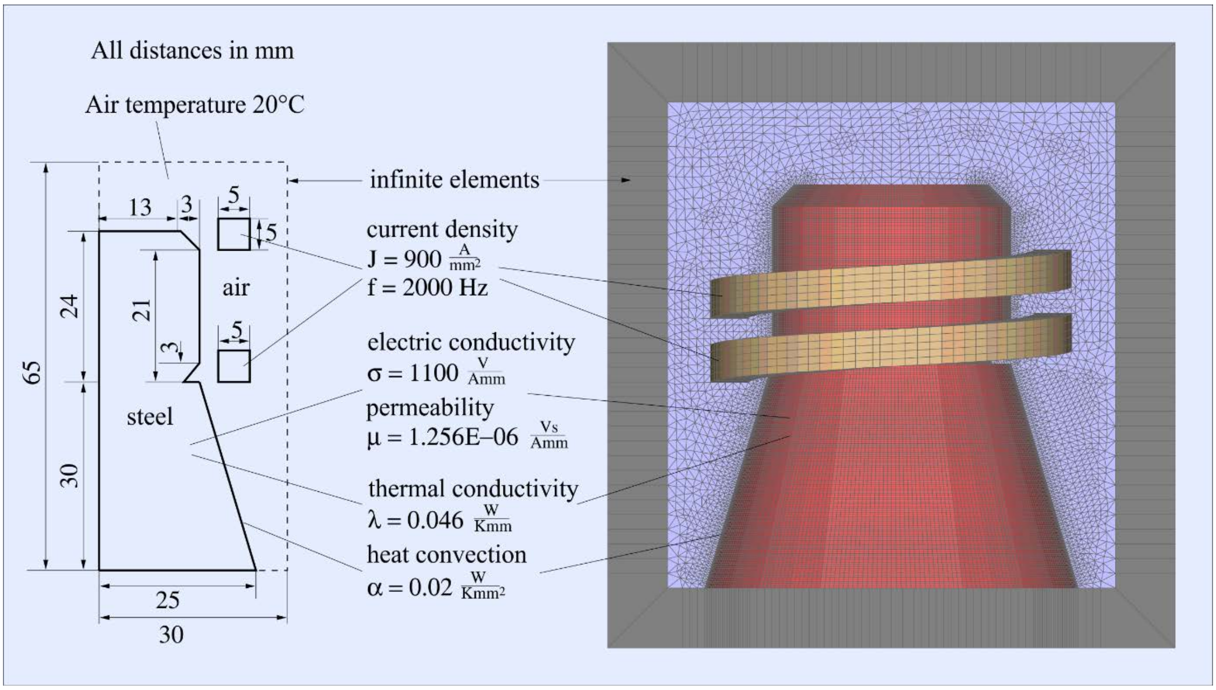

Fig. 1: Model set-up for inductive hardening of a bolt

2 Model

To achieve a unified model for all the intended analysis types, the different types of degrees of freedom have to be taken into account by the same geometric type of finite element. E.g., the solid elements in the bolt have to handle magnetic and electric potential as degrees of freedom beside temperature and displacements. Fig. 2 collects all the information about degrees of freedom for all contributing fields and the related elements in the model.

	Degrees of Freedom	**Elements**
Elektromagnetic field	Potential $\boldsymbol{r} = \begin{Bmatrix} \boldsymbol{A} \\ \phi \end{Bmatrix}$ Magnetic vector potential ***A*** Scalar elektric potential ϕ	Bolt, coil, air, semi-infinite elements at the boundary
Temperature field	Temperature *T*	Bolt, heat convection at the surface
Displacement field	Displacement $\boldsymbol{r} = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}$	Bolt

Fig. 2: Different types of degrees of freedom for the analysis of inductive heating

3 Induction

To calculate the induced current in the bolt, a transient analysis is required under a harmonic alternating current load in the coil. Electric conductivity and permeability are the relevant material properties. Fig. 3 shows the electric and the magnetic fields when they reach their maximum values. The amplitude values are visualized.

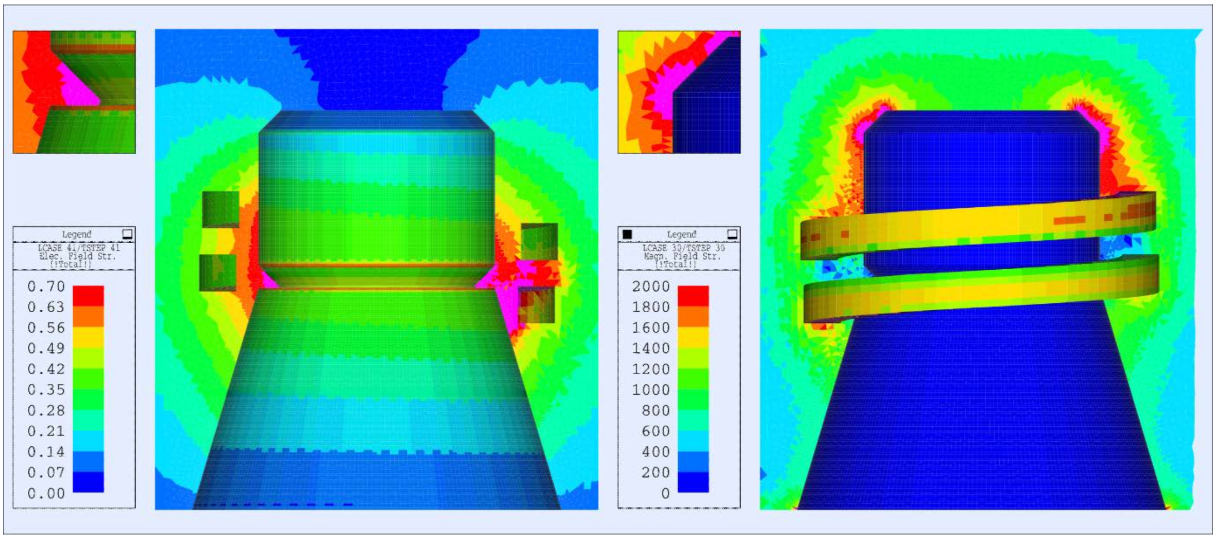

Fig. 3: Electric and magnetic field around the bolt

The current is typically induced only at the surface with a rather low depth. This effect is known as skin effect and for the steel properties given, the skin depth is predicted to 0.34 mm, where the current is already reduced to about one third of the value at the surface. This depth measure is also used as mesh size at the bolt's surface. Fig. 4 shows the induced current in the bolt on the left and the induced heat flux due to this current on the right.

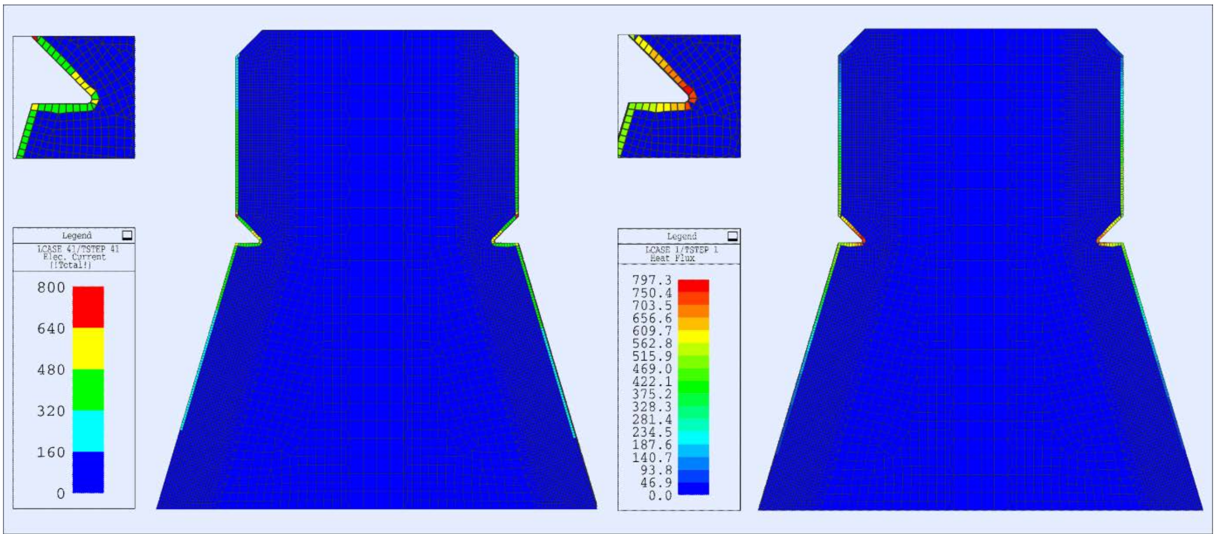

Fig. 4: The skin effect for induced current at the bolt's surface and the derived heat flux

4 Heating up and Quenching

The heating up phase of the process lasts for 0.075s, while the quenching phase has a duration of 1.0s. This quenching is modeled by a high enforced heat convection at the bolt surface of 20000.0 W/Km^2. The temperature after heating up reaches about 950°C and after quenching the maximum temparature is about 70°C. Fig. 5 shows the temperature fields after heating up on the left and after quenching on the right.

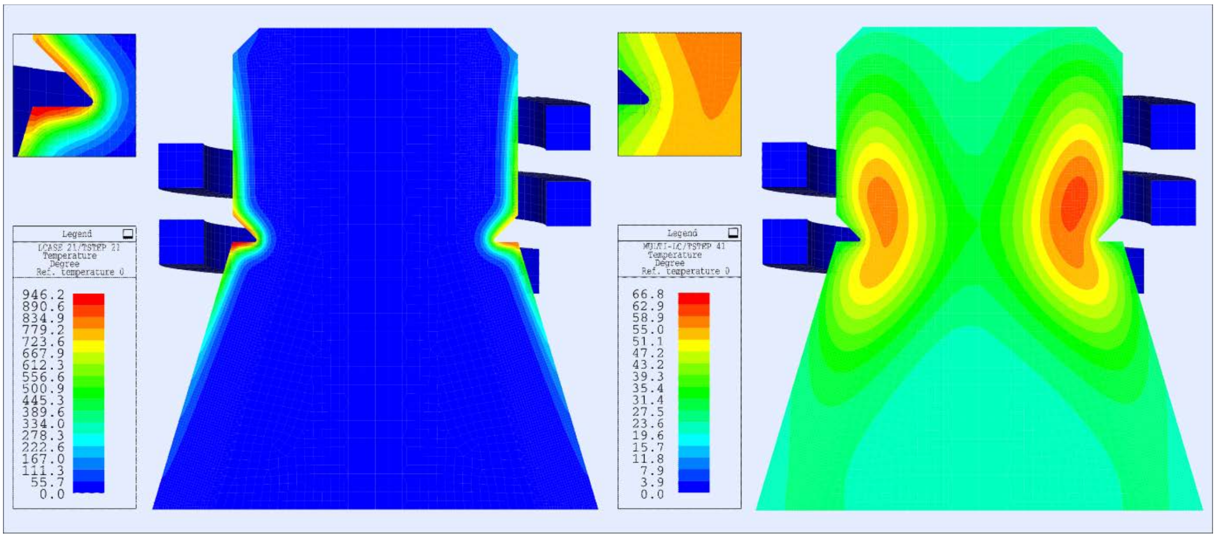

Fig. 5: Temperature fields after heating up and after quenching

5 Stresses and Plastic Strains

The high temperature difference during heating up and quenching cause high stresses in the bolt surface and the area below. A classical material nonlinear analysis is used to follow the process of raising and dropping temperatures. The result is shown in Fig. 6, where the nodal von Mises stresses and the effective plastic strains are shown after quenching.

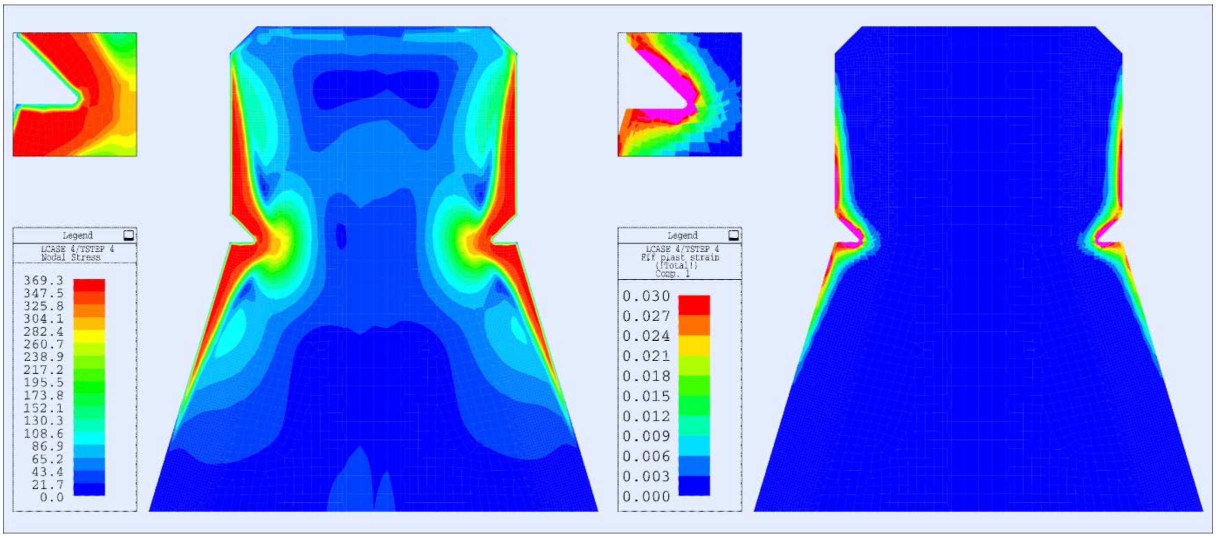

Fig. 6: Nodal von Mises stresses and effective plastic strains after quenching

6 Conclusions

Electrodynamics, thermodynamics, and structural mechanis can be used in one PERMAS model to analyse the inductive hardening process. To this end, PERMAS allows different types of physical degrees of freedom to be used with one element type. In this way, all model data for the whole process are contained in one model. There is no need to map results between different steps of the process when performed with different software. Therefore, there is no loss of accuracy in the analysis process.

The coupled analysis shown allows the preliminary design of the hardening process. In addition, the result of the coupled analysis can be used as inital situation for further analyses under operational loads. Any modifications of the part's geometry are automatically taken into acoount in all analyses.