3D DESIGN OF AN INDUCTOR FOR INDUCTION HEATING USING 2D FEM AND 3D BIEM MODELLING

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Components of mechanical systems often undergo severe duty. They are heat treated in order to increase their lifetime and durability. The goal of this treatment is to transform a surface layer of the material in order to obtain a greater hardness and create a residual stress in this layer. At the same time, it is important to retain ductility in the rest of the component.

Increased hardness is obtained by quickly raising the temperature of the material. Once its temperature reaches the value needed for austenitization, the material is quenched. The rate of quenching must be high enough to effect a martensitic transformation of the material. We will use eddy currents, generated by an electromagnetic inductor, as the thermal source of the process. The advantages of using induction are that the thermal source is easily controlled, and it can be localized in a small depth of material.

In this paper we will present the design of an inductor for the surface hardening of a steering rack. First, we will describe the process. We will then look at the available modelling tools. Finally, we will present the full design of the inductor using these modelling tools.

THE PROCESS

The goal is to harden a steering rack (Fig. #1). For efficiency, the racks are treated sequentially. The optimum method would be to push the racks through an inductor of axisymmetric geometry.

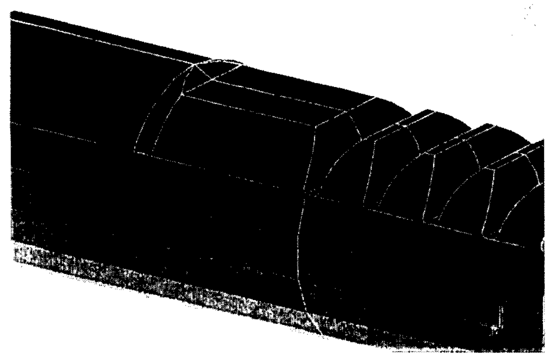

Figure 1: Geometry of the rack

However, using an axisymmetric inductor would allow us to treat only the top part of the teeth of the rack (Fig. #2). We actually need to treat the teeth uniformly from top to bottom. In the complete device, rack and pinion, the maximum stress is applied on the side faces of the teeth. Therefore, special care must be taken in hardening the sides of the teeth. We need an inductor with a more complex geometry that will meet these requirements.

We will save on the design by using modelling tools to optimize the geometry of the inductor instead of building numerous prototypes. From the metallurgical requirements for the process, we find the required temperature distribution in the rack. The thermal sources yielding this temperature distribution are due to eddy currents developed by the field created by the inductor. We will design the inductor to generate the correct field distribution at the

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surface of the rack.

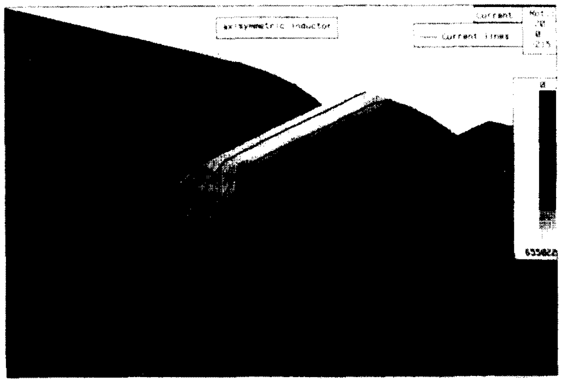


Figure #2: Current yielded by an axisymmetric inductor

Metallurgical data

Temperature to reach

FLUX2D

Distribution of magnetic field along the surface

PHI3D

Geometry of the inductor

Figure #3: Design of the inductor

We are dealing with a difficult problem. First, the geometry of the rack is three dimensional. Then, the hardening process puts to work electromagnetic and thermal phenomena. Moreover, the electromagnetic and thermal phenomena are interdependent: the electromagnetic properties of the material depend on the temperature. Also, due to the frequency of the current source used to achieve the process, the size of the skin depth is very small compared to the size of the rack itself.

THE TOOLS AVAILABLE

To compute the magnetic field distribution from the temperature distribution in the rack, we used Flux2D. To design the geometry of the inductor from the field distribution at the surface of the rack we used Phi3D (Fig. #3).

Phi3D is based on the boundary integral equations method[1][2]. To describe the problem, it is necessary to input and mesh only the surfaces surrounding the media. This makes inputting the geometry very easy. Since the space is not meshed, the inductor can be modified and moved very efficiently.

On the other hand, Flux2D is based on the finite element method. The program is well adapted for computation of coupled magneto-thermal problems[3][4].

MODELLING OF THE 2D PROBLEM

Taking into account the symmetries of the problem, we need to compute the magnetic field on only half a tooth. The frequency of the electric source will be 30 kHz. The material of the rack is non-magnetic. The skin depth at the start of the heating stage is about .3 mm (the external diameter of the rack is 30 mm).

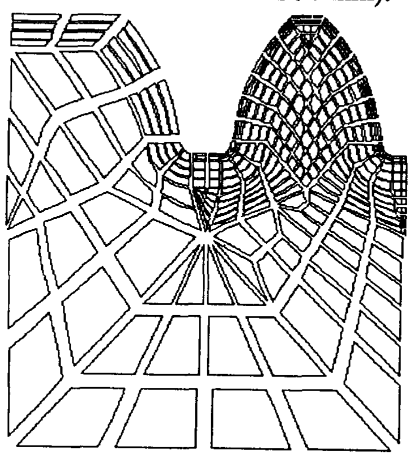


Figure #4: Mesh

Figure #4 shows the finite element meshing of the 2D geometry. Note the three layers of elements within the skin depth.

We want to obtain a temperature of 800°C along the line shown on Figure #5. Also, the tip of the tooth should not overheat.

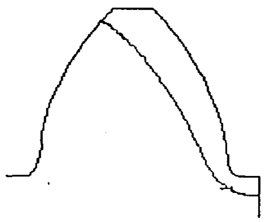


Figure #5: Thermal requirement (800°C)

For the electromagnetic source, we set values of the magnetic field along the outline of the tooth (Fig. #6). Figure #7a shows the power distribution at the beginning of the heat cycle. Figure #7b shows the isothermal lines 400, 600, 800 and 1,000°C at the end of the heat cycle as computed by Flux2D.

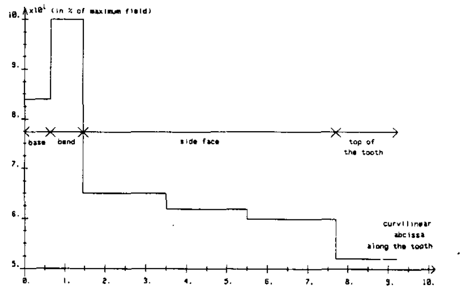


Figure #6 : Distribution of the Magnetic Field

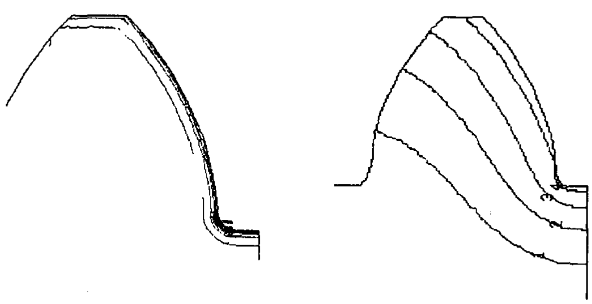


Figure #7a & b: Isothermal lines and power densities.

We need to heat the rack in about 2 seconds. We can verify from figure #7b that the 800 °C isothermal line outlines the region to harden.

3D MODELLING

We just computed the value of the source field along the surface of the tooth. Now we will design the geometry of an inductor yielding the same magnetic field distribution.

The material of the rack is non magnetic. The increase in temperature will only change the resistivity of the material. The average temperature is used to compute the value of the resistivity. The field pattern along the surface will not change much as the temperature of the material rises. Therefore, we can use a program that handles only magnetic problems to design the inductor. Phi3D fulfills this requirement. Also, the steady state AC capability of Phi3D is well adapted to problems with thin skin depth[2].

Once the geometry of the rack is entered and the surfaces meshed, we will try different geometries of inductors. Figure #8 shows the 3D mesh and the location of the inductors. Inductors are described as current lines.

Figure #8: Mesh and Sources

Figure #9 shows the current distribution along the surface of the rack and the lines of current. This distribution was achieved using a shorter version of the optimized geometry of the inductor.

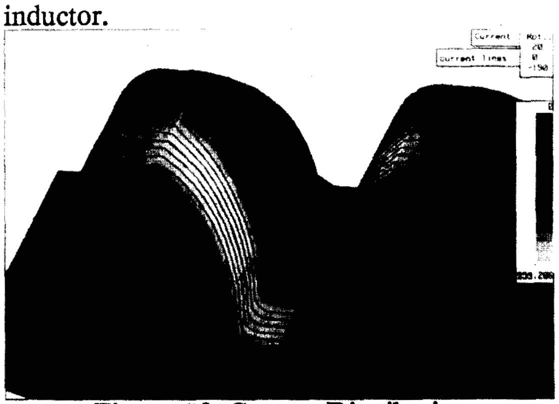
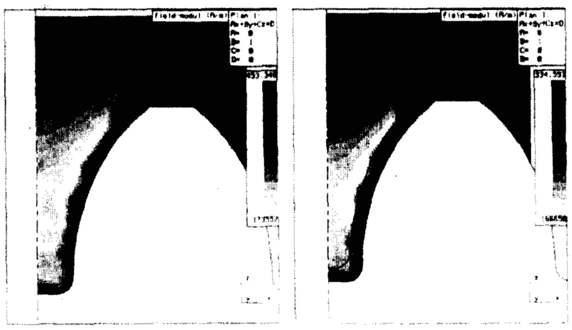


Figure #9: Current Distribution



Figures #10a & b: Magnitude of the magnetic field in an X-section.

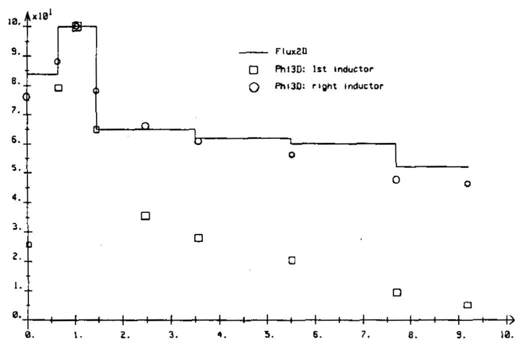


Figure #11: Magnitude of the field along the surface of the tooth (Flux2D, Phi3D).

Although the geometry of the inductor is now more complex, the racks can still be treated sequentially by moving the inductors up and down in order to change the rack to treat.

Figures #10a & b shows the magnitude of the magnetic field achieved for two geometries of inductors. Figure #10a is for the initial geometry, Figure #10b for the optimized geometry. We compare the required source field along the surface as computed in 2D to the field computed in 3D (Fig. #11). The results are satisfactory.

CONCLUSION

We have shown how it is possible to solve a complex problem with available tools (3D coupled magnetic and thermal problem). Neither of the tools themselves is adapted to handle the problem alone. However, by combining the use of two modelling programs and by making some realistic simplifications, we obtained a satisfactory design.

The next step in the design of the inductor would be to study the end effect along the other faces of the teeth.

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