A SIMULTANEOUS INDUCTION HARDENING METHOD OF PINIONS

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This paper proposes a method of simultaneous hardening of pinion teeth using eddy currents. Compared with the individual treatment of pinion teeth the proposed procedure is remarked through its high productivity an uniformity of the treatment. In order to analyse the proposed technology, the thermal diffusion and eddy currents problems must be solved. Numerical results are presented.

1. **INTRODUCTION**

Well known results from the Material Engineering show that the quality of some metallic pieces can be increased by hardening, by heating the piece over the austenitic temperature and by imposing then a certain decreasing speed for the temperature of the piece. Unfortunately, when the hardening process of the whole piece is over, the piece becomes friable, and sometimes it is impossible to be used for what it was designed. For these reasons, it is useful to harden the pieces only in the area that requires a high toughness. Surface hardening provides to the metal pieces the quality of resisting to the galling process, and in the same time, maintaing the elasticity and the mechanical endurance of the whole piece. A modern and efficient way for surface heating can be obtained by inducing eddy currents to a depth that can be controlled by modifying the frequency of the inductor current. The accurate determination of the eddy current distribution involves the solutioning of an intricate problem of the electromagnetic field in quasi-stationary regime, coupled with a thermal diffusion problem. With respect to the piece volume, the heating time must be low enough to avoid the diffusion of the temperature under permitted levels. The evolution of the thermal field depends on the eddy current losses also requires the solutioning of an intricate problem of thermal dissipation. The properties of the piece's manufacturing material depend

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on the temperature, so that the thermal problem goes together with the electromagnetic one.

In the last few years, new analysis methods for the hardening process have been developed, where the numeric analysis of the electromagnetic field is coupled with the analysis of the thermal diffusion. At present, the methods can be applied to all types of geometry and they can take into account the changes for both the electromagnetic and thermal parameters according to temperature. Close to Curie point (normally, being under austenitic temperature), the *B-H* relation is very dependent on temperature, passing from the form characteristic of the iron-magnetic environments to that of the air. For this reason, the eddy's current and thermal diffusion problems are strongly coupled in the Curie point area, and all the methods for the numerical computation are characteristic for these problems revealing a kind of instability.

Commercial programmes packages adopt the pseudo-linear pattern [1], where the *B-H* relation is linear, the magnetic permeability being adjusted according to the maximum or effective value of the magnetic induction. The pattern allows the embracement of both the sinusoidal regime and complex images for the sizes of the electromagnetic field and its equations. The results are acceptable for the specialists. Other refined methods, such as "brute force" (see the FLUX package) or "harmonious balance" [2] are great time and memory consumers and they don't lead to a better accurateness of the solution.

This paper recommend an efficient procedure for hardening the pinions' teeth in eddy currents. The procedure is capable to accomplish high productivity and a more uniform dental treatment with respect to the usual technologies. The recommended solutions are analysed with FLUX-2D package programme.

2. **ELECTROMAGNETIC FIELD PROBLEM**

In the case of 2D structures, the magnetic field problem can be reduced to the determination of a potential vector with a single component, which verifies an equation similar to that of the scalar potential:

$$-\operatorname{div}\left(\nu \operatorname{grad} A\right)+\sigma\frac{\partial A}{\partial t}=C\cdot J_0. \tag{1}$$

where $\nu=\dfrac{1}{\mu}$, and $\boldsymbol{J}_0=kJ_0$ is considerate. The values of C constants, which can be different on disjunct conducting domains, result by imposing the global currents on these sub-domains. The Dirichlet boundary condition for A comes from the boundary conditions imposed to the normal element of the magnetic induction.

$$A = g_A. \tag{2}$$

The Neumann boundary conditions for A result from the boundary condition imposed to tangential component of H:

$$-\nu \frac{\partial A}{\partial n} = f. \tag{3}$$

3. FINITE ELEMENT METHOD

We take:

$$A = A_0 + \sum_{i=1}^{N} \alpha_i \varphi_i, \tag{4}$$

where A_0 is a known component which has Dirichlet boundary condition $A_0 = f_A$, and φ_i are given, independently linear functions, which have a null Dirichlet boundary condition (named "shape functions"). Using Galerkin procedure, we project the equation (1) on test function φ_k and we incorporate it in parts and obtain:

$$\int_\Omega \nu \,\mathrm{grad}\varphi_k \,\mathrm{grad} A \,\mathrm{d}\Omega - \int_\Omega \sigma \frac{\partial A}{\partial t} \varphi_k \,\mathrm{d}\Omega + \int_{S''} f\varphi_k \,\mathrm{d}l = -\int_\Omega J_0 \varphi_k \,\mathrm{d}\Omega + \int_\Omega C\varphi_k \,\mathrm{d}\Omega, \tag{5}$$

we take into account of (4), result equation system:

$$\sum_{i=1}^{N} \left(a_{ki}\alpha_i + a'_{ki} \frac{d\alpha_i}{dt} \right) = b_k, \quad k = 1,2,\cdots,N, \tag{6}$$

where:

$$a_{ki} = \int_\Omega \nu \,\mathrm{grad}\,\varphi_k \cdot \mathrm{grad}\,\varphi_i \,\mathrm{d}\Omega; \tag{7}$$

$$a'_{ki} = \int_\Omega \sigma \varphi_k \varphi_i \,\mathrm{d}\Omega; \tag{8}$$

$$b_k = -\int_\Omega \mu \,\mathrm{grad} A_0 \cdot \mathrm{grad}\varphi_k \,\mathrm{d}\Omega + \int_\Omega \sigma \frac{\partial A_0}{\partial t} \varphi_k \,\mathrm{d}\Omega - \int_\Omega J_0 \varphi_k \,\mathrm{d}\Omega - \int_{S''} f\varphi_k \,\mathrm{d}l + \int_\Omega C\varphi_k \,\mathrm{d}\Omega.. \tag{9}$$

5. **THERMAL DIFFUSION PROBLEM**

The diffusion of thermal field is described by equation:

$$-\operatorname{div}\lambda\operatorname{grad}T + c\frac{\partial T}{\partial t} = p, \tag{10}$$

where c is the volume thermal capacity, λ is the thermal conductibility and p is the power's volume density that transforms itself from an electromagnetic form in heat. To equation (10) we add the boundary conditions:

$$-\lambda\frac{\partial T}{\partial n} = \alpha\left(T - T_e\right) \tag{11}$$

and the initial condition for temperature: $T(0) = T_{\text{in}}$.

The time discretisation of equation (10) is done through Crank-Nicholson technique, and the space discretisation is done through the finite element method.

6. **THE COUPLING BETWEEN THE THERMAL DIFFUSION AND EDDY CURRENTS PROBLEMS**

The material parameters from the eddy currents problem (*B*-*H* characteristic and resistivity) depend on the temperature, while the material parameters from thermal problem depend on the results of both the eddy currents problem (power density) and temperature (thermal capacity and thermal conductibility). For this reason, for each time step adopted for the thermal problem, we have to revert to the eddy currents problem and to the diffusion problem, correcting the material parameters. When the correction is not significant, the next time step is undertaken. If any instability is recorded in time, then the time step is reduced.

7. **APPLICATION**

The simultaneous hardening of pinions' teeth [3] has a few important advantages in comparison with their individual hardening:

– the necessary time for pinion hardening decreases almost N times, where N is the number of pinion teeth;

– for the same value of the current, the supplying tension increases for N times, fact that represents a favourable situation for the achievement of the supplying equipment at high frequency;

– due to the electromagnetic and thermal field periodicity, the obtained hardening is the same for all the teeth;

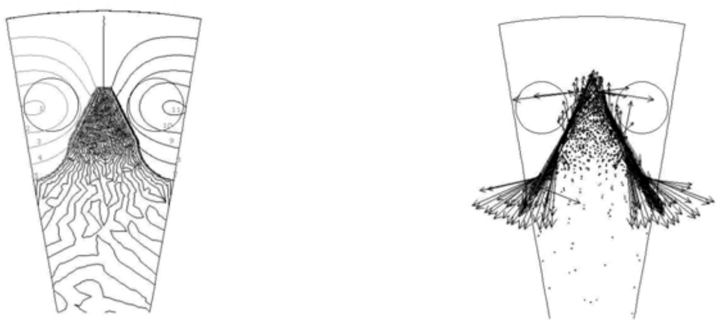
– the heat is generated, so that it couldn’t be uselessly dissipated to the neighbouring teeth; thus, the efficiency of the method is better.

At the gear wheels with big module, a single inductor was accomplished with which a single tooth was hardening at a time. The new method of simultaneous hardening of pinion teeth consists in making a coil system which surrounds all the pinion teeth, similar to a winding for a synchronic machine rotor with *N* poles. Its form is designed so that it easily allows the change of the gear wheel with another. Thus, in opposition to the case of the electrical machine, the frontal area of the coil belonging to the heating system has the aspect of a funnel that allows the pinion insertion (Fig. 1).

Fig. 1 – Hardening device with high productivity.

7.1. RESULTS IN CASE OF THE INDUCTOR WITH CIRCULAR SECTION CONDUCTOR

We have chosen a current density of 15 A/mm^2 and a frequency of 8000 Hz. For the structure with circular inductor, a current of: 2649.45 A results, because the area of the circular section inductor is of 176.63 mm^2.

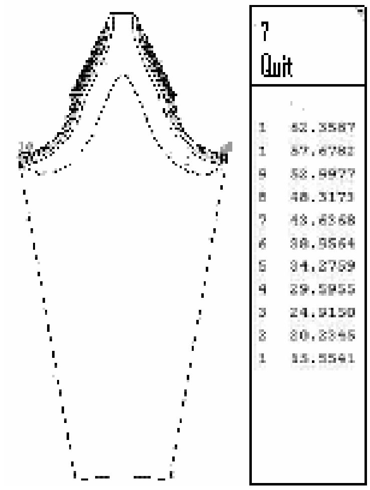


Flux lines for inductor with circular conductor. Magnetic induction for faze 0 at time t = 21.28 s.

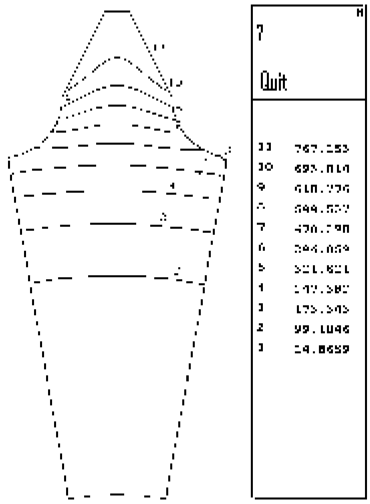
Fig. 2 – Field lines

For the gear wheel with circular conductor we have the field lines and the flux density given in Fig. 2, traced for time t = 21.28 s, at the initial faze 0.

The temperature map for time 0.1 and 21.28 s is drawn in Fig. 3.



Temperature map from tooth at time 0.1 s.

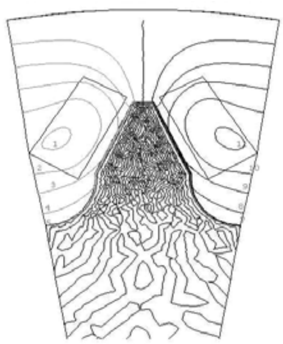


Temperature map from tooth at time 21.28 s.

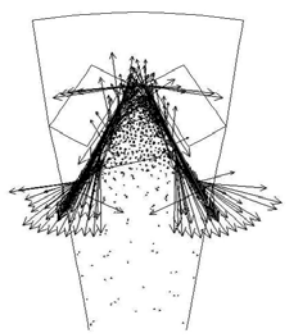
Fig. 3 – Temperature map from tooth at time 0.1 and 21.28 s.

7.2. RESULTS IN CASE OF THE INDUCTOR WITH RECTANGULAR SECTION CONDUCTOR

The same diagrams are obtained for the rectangular inductor (Figs. 4 and 5).

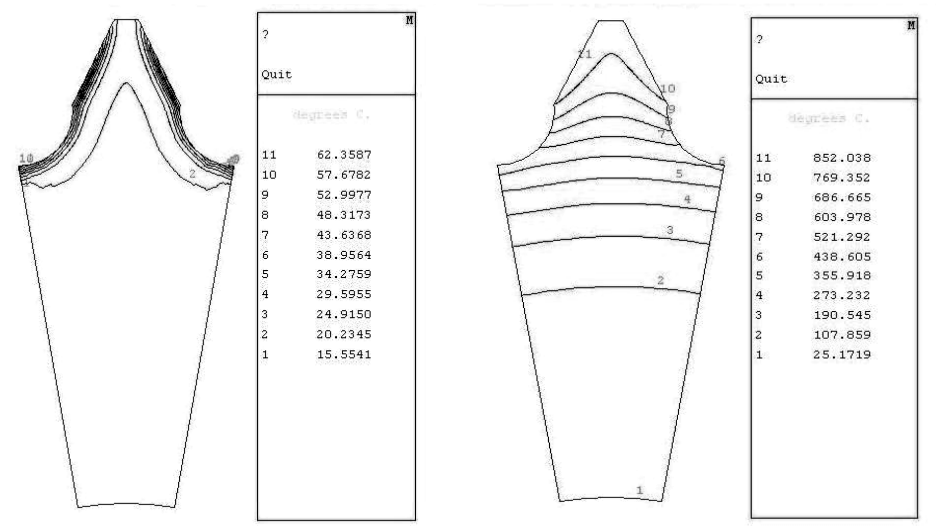


Flux lines for inductor with rectangular conductor.



Magnetic induction for faze 0 at time t = 21.28 s.

Fig. 4 – Field lines.



Temperature map from tooth at time 0.1 s. Temperature map from tooth at time 20.78 s.

Fig. 5 – Temperature map from tooth at time 0.1 and 20.78 s.

8. **CONCLUSIONS**

This paper propose the simultaneous heating of the pinions teeth in order to accomplish the hardening process with an increase of the quality and productivity of the resulted products.

In this matter was performed an numerical computation of the surface heating process to accomplish the hardening of pinions teeth by electromagnetic induction.

This computations for the coupled electromagnetic and thermal field problem allow us the optimization of the heating process in order to accomplish the pinions hardening, and also the optimal design of the simultaneous hardening equipment for pinions, witch accomplish the electromagnetic power transfer to the pinions which are hardened with maximum efficaciousness.

The numeric modelling of the superficial hardening process by the help of the eddy currents is a complex problem, where are solved simultaneously two field non-linear problems: one of electromagnetic field and the other one of thermal diffusion. The non-linearity characteristic of the eddy current problem is due to the *B*-*H* non-linear relation, while the non-linearity of the thermal problem is due to the dependence of the thermal parameters on temperature (thermal conductibility, thermal capacity, coefficient of surface thermal transfer).

The coupling of the two problems results from the strong dependence of the relation *B-H* with temperature in the case of the electromagnetic field problem, respectively from the thermal field source, given by Joule losses, in the case of the thermal diffusion problem. The non-linearity of *B-H* relation is solved by admiting the pseudo-linear model, where, the magnetic permeability being corrected iteratively according to the magnetic induction.

The great advantage of the model results from the possibility to adopt both the sinusoidal regime and complex images, the numeric form of field equation leading to an algebraic equation system with complex coefficients.

The coupling of these two field problems is solved by time discretisation procedure, where at each time step undertaken, the iterative correction of electromagnetic and thermal parameters is made.

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