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THE HEATING OF A DIAPHRAGM SPRING USING INDUCTION TECHNIQUE: PARAMETRIC MODELING

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The configuration and work of a system for local heating of a diaphragm spring by induction technique have been studied. The problem-oriented 3D model, developed using ANSYS APDL, made possible to analyze effects of geometric, electrical and positional parameters on temperature distribution over the considered product in its electromagnetic heat treatment. In particular, the temperature fields were obtained varying spring finger number and length, as well as control of finger bend by setting up a heating mode. The main connections between the final temperature distributions and the geometry of the heated product were established. The heating was generated using both longitudinal and transverse magnetic fields.

Keywords: induction heating, numerical simulation, optimization, heat treatment, diaphragm spring

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ПАРАМЕТРИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА НАГРЕВА ДЕМПФЕРНОЙ ПРУЖИНЫ ИНДУКЦИОННЫМ МЕТОДОМ

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Исследованы конфигурация и работа системы для локального нагрева демпферной пружины индукционным методом. Проблемно-ориентированная 3D модель, разработанная на базе ANSYS APDL, позволила изучить влияние геометрических, электрических и позиционных параметров на температурное распределение по рассматриваемому изделию при его электромагнитной термообработке. В частности, получены температурные поля при вариации количества и длины пальцев демпферной пружины, при регулировании зоны отгиба пальцев с настройкой режима нагрева. Установлены основные связи конечных температурных распределений с геометрией нагреваемого изделия. Нагрев осуществляли с использованием как продольного, так и поперечного магнитных полей.

Ключевые слова: индукционный нагрев, численное моделирование, оптимизация, термообработка, демпферная пружина

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Introduction

Numerous studies have been dedicated to electromagnetic and thermal processes occurring induction heat treatment of products, focusing, in particular, on products with rotational symmetry. For example, heating of metal workpieces shaped as disks or rings is widely used in different industrial technologies; it is particularly important for design of induction coils [1–10].

Most cases of heating require either achieving a uniform temperature distribution throughout the entire volume of the object or maintaining a local temperature region. A classical spiral or loop induction coil is typically used as a disk, located under the object. The configuration of the induction system can be single or multi-turn; eddy currents in the disk then have rotational symmetry. This provides an additional opportunity to control the temperature field by rotating the disk. Eddy currents have a dead zone in the center in this problem statement, and different cooling conditions should be expected in the heated area during heat treatment of a disk with a complex profile. After heating or cooling the product, a heterogeneity of the temperature field naturally appears.

The characteristics of a diaphragm spring depend on its geometric dimensions. The operational characteristics of the mechanism equipped with such a spring (for example, a car clutch) generally change as well.

Since the geometry of the workpiece cannot be altered to achieve the goals of heating and obtain the desired parameters for residual stresses, calculations establishing the necessary level of strength and elasticity are performed first [1]. The optimal shape of the diaphragm spring serves to distribute loads (dynamic and static, constant and thermocyclic, bending loads); heat treatment of this spring is aimed at achieving a balance between the necessary strength in the fingers and the ductility of the diaphragm spring disk. Because of this, not only the geometric parameters of the workpiece but also the technology by which it is manufactured are important for selecting the temperature for heat treatment.

This paper presents a numerical study of induction heating of diaphragm springs for trucks. Such springs are produced by die stamping. The clutch assembly of the truck is hardened by a single stroke with the stamping die, modeling the workpiece into the required shape; the assembly is then heated to 450 °C for subsequent tempering.

Parametric studies of electrothermal processes

The standard number of fingers (Fig. 1) located around the circumference of the diaphragm spring disk was 24, 20, 18, and 12.

The given system is symmetric, so rather than simulate the complex geometry of the workpiece, we decided to simulate only a single section using azimuthal periodicity of the workpiece structure.

We used the following initial data for simulating the diaphragm spring:

Number of fingers..................12, 18, 20, 24
Corresponding computational domains
deg(min)..................15(0), 10(0), 9(0), 7(5)

The experimental data from [2] is used for the rest of the initial data (design and electrical parameters of the induction coil, mutual positioning and heating time), the heating problem, the criterion for assessing whether the target set (the given temperature level) is achieved.

The nonlinear coefficients used in the simulated system are related to the dependences of the properties of metal workpieces on temperature and electromagnetic field strength, which explains the relationship between electromagnetic and thermal problems. We provided a detailed description for the algorithm for direct simulation of the problem with a coupled electrothermal solution of induction heating of a disk in [3, 9].

Fig. 1 shows a schematic of the diaphragm spring. The initial computational domain *2* is a flat sector of a circle with a central angle of 9^{o}. This means that the basic design of the diaphragm spring has 20 fingers. The estimated time required for calculation with the given accuracy is thus reduced by 40 times. The total height of the unloaded spring is taken equal to the height of the loaded one. In other words, the workpiece does not have the curvature necessary for operation, and has a flat shape under load. This aspect is not particularly important for the heat treatment procedure; actually, in order to maintain uniform local heating, the turns of the heater should be located:

a) on one axis;

b) strictly parallel to the plane relative to the heating zone.

An arrangement complying with the above requirements allows to adjust the input power by changing the current in the induction coil, turn pitch and the width of the air gap.

The parametric study is performed based on the developed parametric 3D model (Fig. 2).

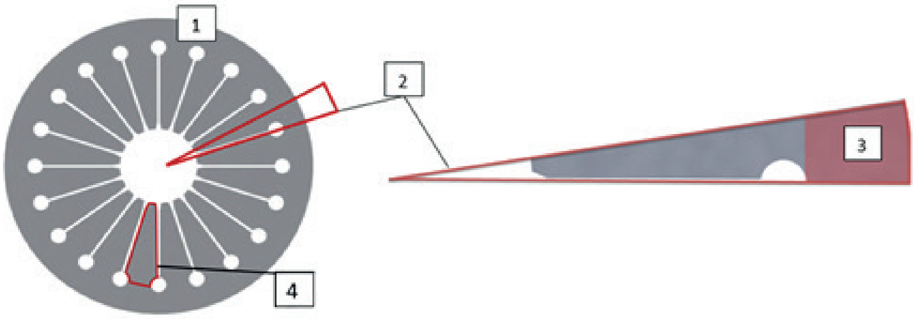

Fig. 1. Schematic problem statement:
general view of workpiece *1;* simulation zone *2;* heating zone *3;* finger *4* of diaphragm spring

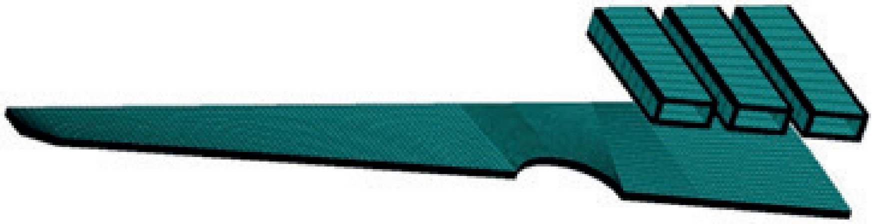

Fig. 2. Finite-element 3D system: induction coil *1*, diaphragm spring *2*

It is assumed that the bend zone of the fingers is the most critical in terms of hot spots appearing. The effect that the shape of the finger bend had on the temperature field was estimated at the first stage of the study to account for this risk. Fig. 3 shows a comparison of calculated temperature distributions in the workpiece for poor and desirable quality of processing in the finger bend. The workpiece was heated in a longitudinal magnetic field.

Simulation allowed to estimate the probability with which hot spots appeared in the finger bend, using a configuration similar to that described in [2, 3] for the induction coil, where it was used to heat a disk with a simple profile. According to our estimate, the highest density of induced currents should be reached in the finger bend zone due to random walks of eddy currents. Because the workpiece has a complex shape, the heat dissipation conditions vary and depend on the measurement point. The edges of the disk have the best heat dissipation due to their small thickness, and this prevents overheating in finger bend zones. Comparing our experimental data [2] and the results of numerical simulation, we can confirm that the final temperature profile on the surface in the heating zone is satisfactorily uniform with a minimal temperature difference around the disk circumference.

We studied the heating process based on the developed parametric finite-element 3D model, taking into account the main factors affecting the temperature field by varying the current system parameters. This study included the following factors affecting the temperature distribution of the workpiece:

overall dimensions of the diaphragm spring (Figs. 4–6);

number of fingers of the given spring when regulating the computational domain (Figs. 4–6);

heating in a transverse magnetic field; anti-parallel connection is set for the turns of the induction coil for this purpose (Fig. 6).

Analysis of the obtained simulation data allowed us to draw the following conclusions.

1. The effective current affects only the maximum temperature level but not the temperature distribution.

2. Making the fingers of the diaphragm spring longer improves heat dissipation from the heating zone, which ensures a high temperature difference and provides a decrease in temperature relative to the target temperature level set.

3. Regulating the number of fingers by varying the computational domain leads to qualitative change in the generated temperature field.

4. The dimensions of the diaphragm spring (outer diameter, disk thickness, width of its heating zone) play a significant role in generating the temperature distribution. The increase in mass of the workpiece is accompanied by an increase in the energy input required to ensure heating to a given temperature level, and vice versa (its decrease is accompanied by a decrease in energy input). For example, a source power of 44 kW is required to provide effective heating to the required temperature level for a workpiece with a diaphragm spring with an external diameter of 420 mm, a thickness of 3 mm, a frequency of the heating electromagnetic field of 2.5 kHz, and an air gap of 10–11 mm between the workpiece and the induction coil; power of 15 kW is sufficient if the diameter is reduced to 268 mm.

5. A uniform temperature distribution over the given area in the range of the target temperature level can be achieved by induction heating in a longitudinal magnetic field.

The study has allowed to develop practical recommendations for optimizing the heating process. In particular, we recommend to use rounded chamfers in finger bend zone in order to avoid heat concentration and hot spots.

Modifying the properties of the material when selecting the heat treatment temperature is of great interest for calculating the nonlinear operating characteristic of elasticity of materials in a wide temperature range. Treatment temperatures differ depending on the grade of steel and its purpose, so the mechanical properties of the heat-treated workpiece obtained can vary significantly. This is true for a number of technologies: hardening, forging, annealing, normalizing, tempering, as well as combinations of different heat treatments (for example, preliminary heating – quenching – tempering, normalizing – tempering, quenching – self-tempering, quenching – aging, etc.). If necessary, study and analysis of specific cases should be carried out in advance to optimize the properties of the material for a given purpose. The temperature and the heating zone for tempering should be determined taking into account the required properties of the material.

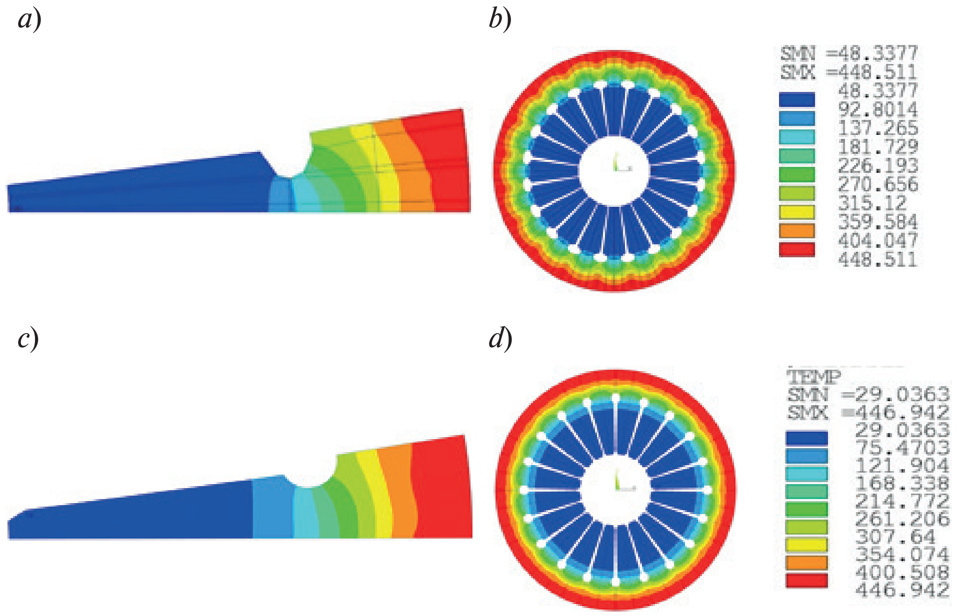

Fig. 3. Final temperature distributions over computational domain of 9° (*a*, *c*) and over workpiece (*b*, *d*) after heating in longitudinal magnetic field with poor (*a*, *b*) and desired (*c*, *d*) surface treatment of diaphragm spring in finger bend zone.
Diaphragm spring has 20 fingers

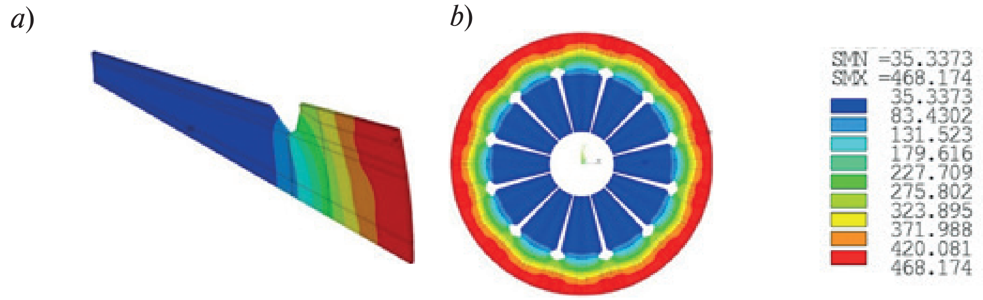

Fig. 4. Final temperature distribution after heating of diaphragm spring 405 mm in diameter in longitudinal magnetic field with effective current of 300 A: computational domain *a,* 15°, complete finite-element solution *b*
Diaphragm spring has 12 fingers

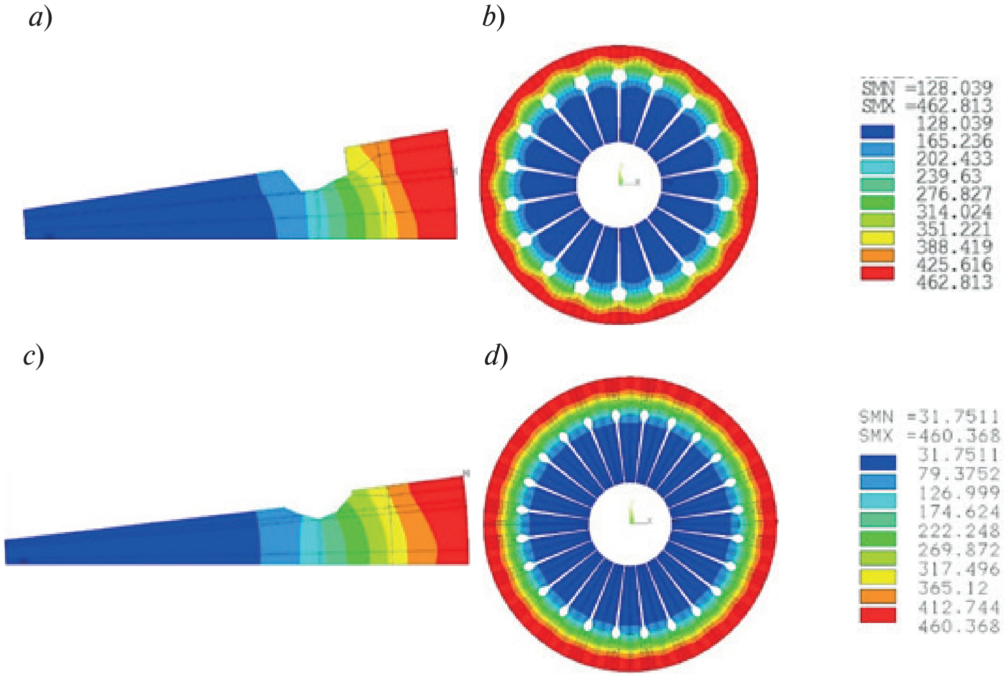

Fig. 5. Final temperature distributions after heating of diaphragm spring 350 mm in diameter in longitudinal magnetic field with effective current of 185 A (*a*, *b*) и 288 A (*c*, *d*)
Computational domains are 10°0’ (*a*) and 7°5’ (*c*)
Diaphragm spring has 18 (*a*, *b*) and 24 (*c*, *d*) fingers

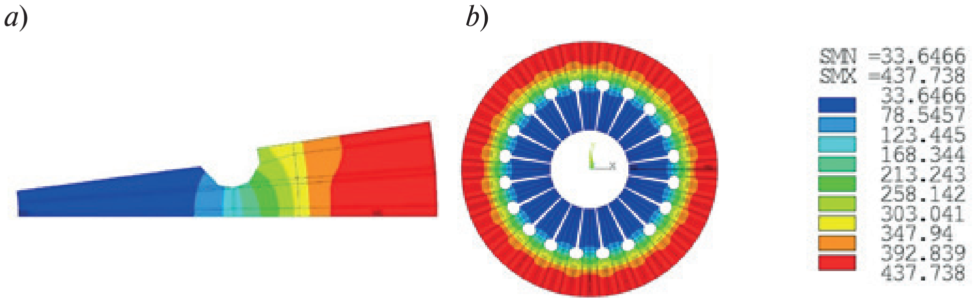

Fig. 6. Final temperature distribution after heating of diaphragm spring 405 mm in diameter in longitudinal magnetic field with effective current of 450 A
Computational domain is 9°
Diaphragm spring has 20 fingers.

Conclusion

Parametric modeling of induction heating of a diaphragm spring was successfully used to study and search for geometric, positional and electrical configurations of the system comprising an induction coil and a workpiece for solving the problem on local heating of the diaphragm spring for tempering. The model developed can be applied to searching for optimal system configurations in order to perform induction heat treatment of diaphragm springs in a wide range of typical sizes, as well as metal blanks shaped as disks or rings, and other axisymmetric metal workpieces with simple and complex profiles.

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