DOI: 10.18721/JPM.12202
УДК 537.856

DEVELOPMENT OF INDUCTION SYSTEMS FOR DISK HEATING

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The paper presents the experimental and numerical results obtained by the induction heating a steel disk. This study has been aimed at realizing the local uniform heating the disk at minimum temperature departure from 450°C. The system-of-interest included 3-turn inducers and a steel disk heated up. The computer-based investigation results were implemented at a laboratory mock-up. The temperature distribution over the disk material and its changes were recorded by a infrared camera. Simulation of electromagnetic and thermal processes occurring in heating a rotating disk-shaped work piece was carried out using ANSYS APDL base. A comparison between the obtained numerical data and experimental one showed a disagreement of about 5 %. It pointed to an adequacy of simulation carried out. A detailed analysis of the disagreement sources was made.

Keywords: induction heating, electrothermal task, numerical simulation, heat treatment, heating with rotation

Citation: Mannanov E.R., Galunin S.A., Nikanorov A.N., Nacke B., Kozulina T.P. Development of induction systems for disk heating, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 12 (2) (2019) 23–31. DOI: 10.18721/JPM.12202

РАЗРАБОТКА ИНДУКЦИОННЫХ СИСТЕМ ДЛЯ НАГРЕВА ДИСКОВ

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В статье представлены экспериментальные и численные результаты, полученные при нагреве стального диска индукционным методом. Исследование направлено на обеспечение локального равномерного нагрева диска при минимальном отклонении температуры от °450С. Рассматриваемая система включала трехвитковые индукторы и нагреваемый металлический диск. Результаты компьютерных исследований были реализованы на лабораторном макете. Температурное распределение по материалу диска и его изменения регистрировались с помощью тепловизора. Моделирование электромагнитных и термических процессов при нагреве вращающейся заготовки в форме диска выполнено на базе программного пакета ANSYS APDL. Сравнение полученных численных результатов с экспериментальными данными показало, что расхождение между ними составило около 5 %, что указывает на адекватность выполненного моделирования. Проведен детальный анализ источников отклонения модели от экспериментальных данных.

Ключевые слова: индукционный нагрев, численное моделирование, термообработка, нагрев вращением

Ссылка при цитировании: Маннанов Э.Р., Галунин С.А., Никаноров А.Н., Наке Б., Козулина Т.П. Разработка индукционных систем для нагрева дисков // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2019. Т. 2 № .12. С. 23–31. DOI: 10.18721/JPM.12202

Introduction

Numerical methods are very efficient and straightforward, yielding highly accurate results, which is why they are widely used for constructing induction heating systems. These methods allow to use automatic parameterization, eliminating extremely high costs for a probabilistic range of experimental trial-and-error procedures. However, while reproducing all factors affecting metal heating in an electromagnetic field can improve the quality of the process and, accordingly, produce better results, it also considerably complicates the problem statement.

Parameters of nonlinear properties of materials depending on temperature should necessarily be considered to correctly reproduce the experimental results in numerical solution of the heating problem. Besides, magnetic permeability μ depends on the magnetic field resulting from magnetic saturation.

The nonlinear behavior of materials means that the problem should be solved in the time domain instead of the simpler data processing in the frequency domain.

The frequency of the current passing through the material can reach high values (up to hundreds of kHz for induction hardening), leading to significant fluctuations of the magnetic field per second. Thus, a periodic electromagnetic solution can be obtained for a short time interval, while the temperature distribution varies over wider time intervals (in seconds). This implies that the distribution of temperature over the material sample depends on the average flux density of the magnetic field. If μ is variable, its value can be updated over every short period of time while preserving computational efficiency, but this inevitably leads to unnecessarily lengthy computations.

The rapidly changing source term in the heat equation, expressing the specific power of internal heat sources, can be replaced by an average value over one period of electric current, calculated from the previously obtained value of the magnetic field, depending on time. This solution is optimal for updating the values of physical parameters characterizing the properties of materials taking into account the new temperature values in the grid nodes.

Numerical simulation

The goal of this study has consisted in maintaining local uniform heating of the disk with minimal temperature deviation from 450°C. This temperature value was chosen based on the results of [7], giving the data obtained after tempering a through-hardened metal sample 3 mm thick.

Each study developing new electrical tech-

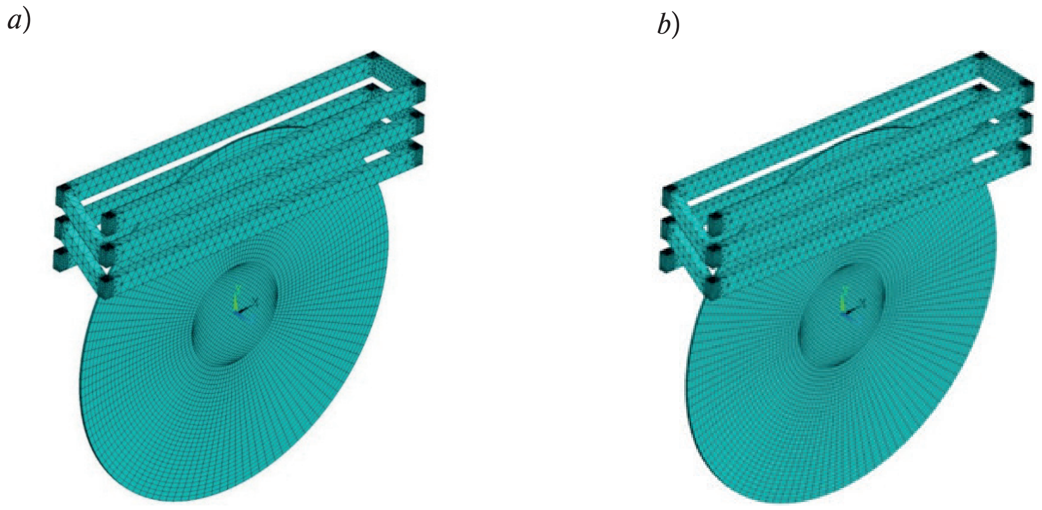

Fig. 1 .3D models of induction heating system in longitudinal (*a*) and transverse (*b*) magnetic fields nologies or modernizing existing ones requires experimental verification. The results of computer studies [1—6] were tested using a laboratory model. A infrared camera was used as a tool for monitoring the temperature variation. The emissivity was set to 0.95 in the software. The temperature range was set from 200 to 1200°C. This way, the sensitivity of the device could be increased in the final temperature zone of 450°C.

Systems developed using the ANSYS APDL software package are 3D models of induction systems for simulating coupled electromagnetic and thermal problems of disk heating. The given system includes three-turn induction coils and a heated metal disk. The disk is made of hardened steel and has the following main dimensions: outer diameter of 410 mm, thickness of 3 mm. The operating frequency of the system is 2.5 kHz. A constant power was maintained in the object during heating. Air is the ambient environment; it is numerically described as a non-magnetic non-conductive medium that does not contain sources generating the electromagnetic field.

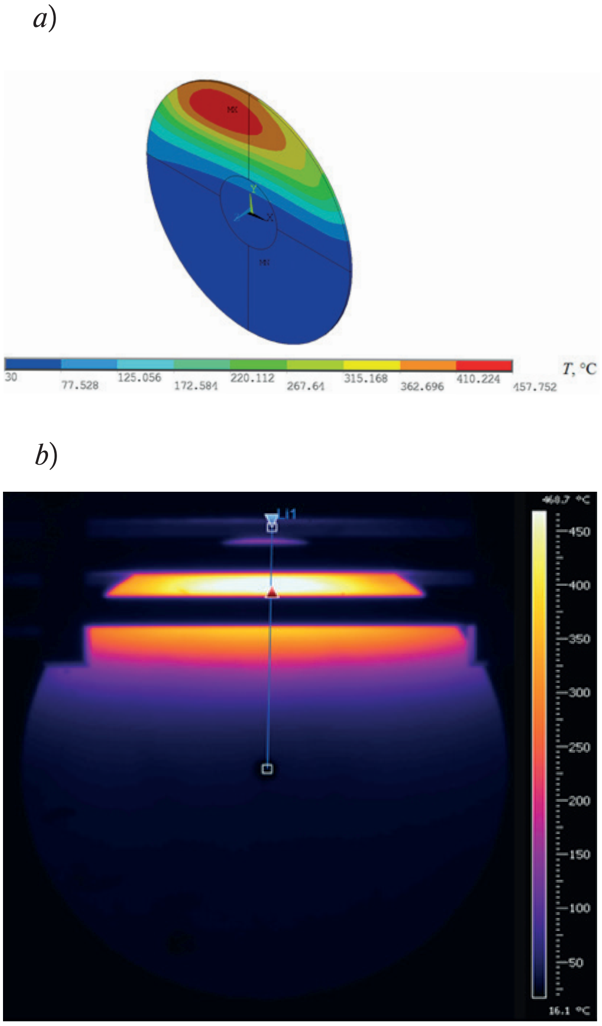

Fig. 2. Comparison of simulation results (*a*) with experimental data (*b*); obtained for temperature distribution over workpiece surface with stationary disk heating in high-frequency longitudinal magnetic field; *b* is the straight line passing from the edge of the disk to its center indicating the direction along which the temperature was measured; the dark triangle indicates the maximum temperature on the surface of the disk

The penetration depth of the current in steel depends on its brand, and was taken in the range of 1.5—0.77 mm for the current frequency of 2.5 kHz, while the relative magnetic permeability μ was taken in the range of 10—40.

As is known, highly efficient tempering is achieved if steel is heated to a depth exceeding its hardening depth. Volumetric induction heating with a small temperature difference across the cross-section is maintained due to a relatively low heating rate. Uniform temperature can be maintained in the given area both due to high thermal conductivity of the heated object, and by varying the time interval required for heating due to small thickness of the workpiece. The given temperature level can be also reached by using other frequencies; in that case, the temperature distribution over the disk surface would be different from the initial one provided that the initial data are unchanged. Additionally, assuming that a sample made by stamping has a complex profile, hot spots may appear if frequencies above 2500 Hz are used to heat such a sample for subsequent tempering.

The geometric shape of the induction coils and the positioning of the heated object fully replicate the actual samples in numerical models. The workpiece is attached to the torque transmission system of torque connected to the electric motor. Eddy currents generate heating (that is local by default) of an electrically conductive workpiece under the coil, but this phenomenon can only be detected with a infrared camera on the surface. This is the reason why numerical simulation is necessary in this case.

The results of the first stage of the study are shown in Figs. 1—3. The 3D model is partitioned into a finite element mesh in the following manner: there are five partitions per each millimeter of the disk thickness; the finite elements of the mesh along the disk diameter are larger but their size still makes it

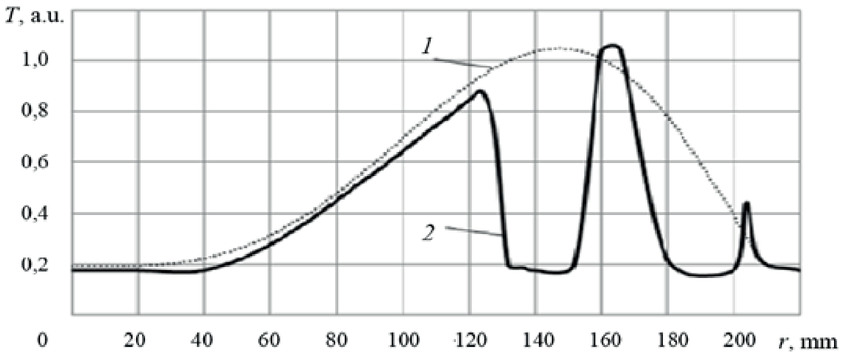

Fig. 3. Final temperature profile along workpiece radius
according to results of numerical simulation (*1*) and experiment (*2*)

possible to obtain fairly satisfactory results. We managed to plot the relationships between the main parameters and to assess the fit of the numerical results to the experimental data.

Electromagnetic and thermal characteristics, namely the relative magnetic permeability, resistivity, thermal conductivity, heat transfer coefficient and heat capacity are non-linear and depend on both the temperature of the hardened steel disk and the ambient temperature. The density of the disk material is assumed to be constant and uniform.

The purpose of the model was to solve the coupled electromagnetic and thermal problems, taking into account rotation, nonlinear magnetic permeability μ and the algorithm for updating data during dynamic temperature variation. The principles by which the model was constructed are described in detail in [4].

Comparison of experimental results and numerical simulation is shown in Fig. 2.

There are several objective reasons for the discrepancy between the simulation and the experimental data. Sharp dips in the temperature distribution along the workpiece radius (Fig. 3) are explained by the fact that the infrared camera was placed at some distance from the heating system. In the specific example, these dips depend on the temperature at the surface of the water-cooled turns of the coil. Because the workpiece was partially located inside the coil, there was no other way to measure the temperature.

We simulated the rotation of the disk at the second stage of the study. Heating to a temperature of 450°C was reached in 30 s with the workpiece rotated at a speed of 18 rpm (Figs. 4 and 5). The graphs are based on averaged results.

The heating time was selected assuming

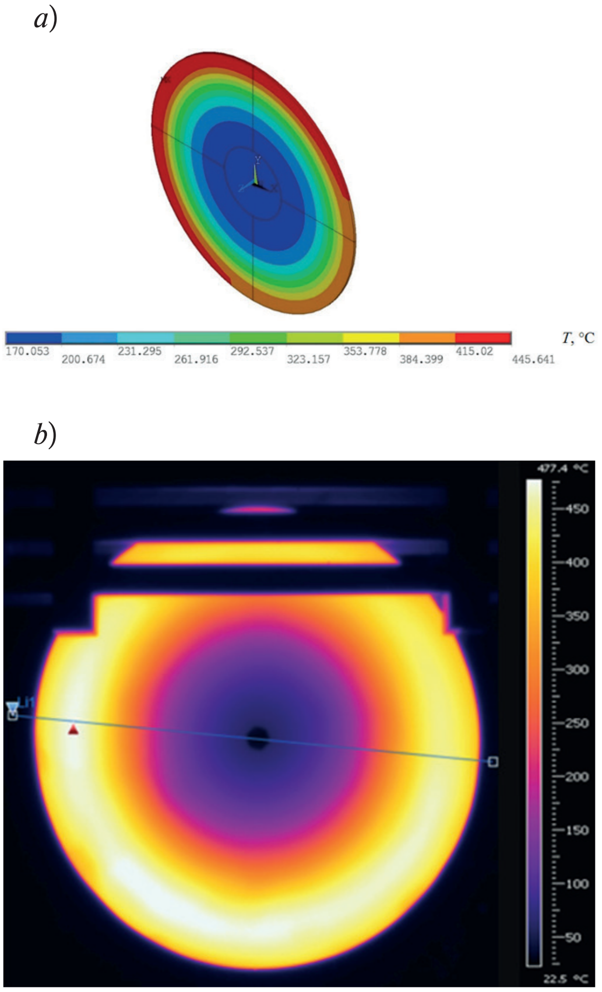

Fig. 4. Comparison of simulation results (*a*) with experimental data (*b*); obtained for temperature distribution over workpiece surface with disk heated by rotation in high-frequency longitudinal magnetic field; *b* is the straight line passing through the center of the disk indicating the direction along which the temperature was measured; the dark triangle indicates the maximum temperature on the surface of the disk

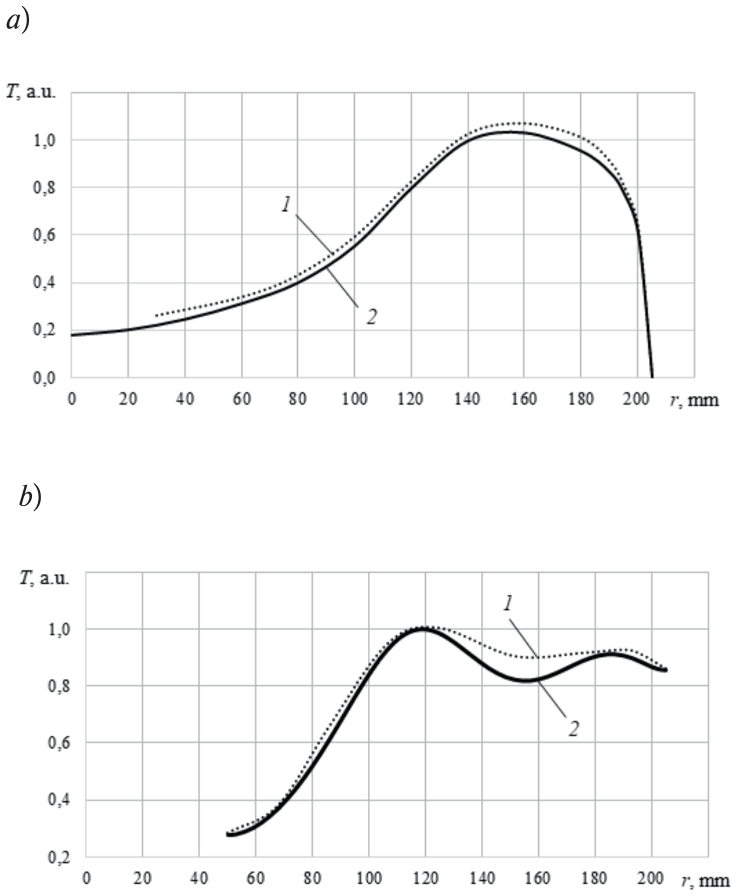

Fig. 5. Temperature profiles on workpiece surface along the radius with disk heated in the longitudinal (*a*) and transverse (*b*) magnetic fields: *1* corresponds to simulation results, *2* to experimental data

that tempering is done for a metal product. Tempering temperature has a significant effect on mechanical properties during high-frequency hardening. As mentioned above, this temperature was chosen based on the results of [7], presenting the data obtained after tempering a through-hardened metal sample with a thickness of 3 mm. A stable temperature field and, as a result, high strength, ductility and toughness of the metal can be maintained at a moderate heating rate. A further increase in tempering temperature inevitably leads to a decrease in strength and an increase in the toughness of the product.

The final temperature distribution at a low rotational speed of the metal disk is induced by thermal conductivity of the material and heat losses from its surfaces. The results obtained are in agreement with the data of [8–10], describing dependences of the allocated additional power in the disk on the rotational speed.

As seen from the data in this study, due to radiative heat losses, the edges of the disk have a lower temperature relative to the required level, while the maximum temperature along the disk radius is shifted towards the center of the heated sample.

In our simulation, the metal disk was heated through for tempering to account for the effects that the operating frequency and the construction of the induction coil system had on the disk's temperature profile. This made it possible to minimize the temperature difference over the cross-section of the disk in the heated zone. However, we did not take into account the presence of a hardened layer in the numerical study. We can predict without running a simulation that in practice this may manifest as an uneven decrease in hardness along the radius of the disk but the hardness can be reduced in an optimal manner.

The discrepancy between the numerical results and the experimental data is about 5%, which indicates that the simulation we have carried out is adequate.

The natural construction of the heating system also includes a magnetic core, which allows to use a lower electromagnetic field frequency by controlling the pole pitch of the coil.

The results obtained indicate that the proposed induction system is sensitive to variation in geometric parameters such as coil geometry and position of the turns relative to the workpiece, as well as to variation in electrical parameters. Therefore, there is an optimal configuration of parameters allowing to achieve the best result, that is, uniform local heating of the product in the permissible range of temperature deviations from the given value in the shortest heat treatment time.

The study showed that non-standard solutions open up additional opportunities for regulating the heating process and improving the efficiency of heat treatment. Thus, the key step in improving the efficiency of induction systems for heating metal products by rotation is modernizing the existing induction heating systems and developing new ones based on automated optimization of geometric, positional and electrical parameters (combined with computer simulation). This should successfully solve the related physical problems during heat treatment, construct the shape of induction coils, select the optimal mode of operation, incorporate the properties of new materials in the design of the developed systems, produce reliable estimates for devising non-standard solutions to reduce material costs.

Conclusion

We have constructed problem-oriented 3D models of induction systems in the ANSYS APDL software package in order to calculate the coupled electromagnetic and thermal problems. The models developed have been tested and verified experimentally. The obtained results can be successfully applied to analyze and solve electrothermal problems for constructing induction systems and for parametric search of optimal configurations of these systems. In turn, optimal characteristics should ensure high quality of the final product and its maximum yield, minimum cost of equipment and maximum total efficiency.

Potential applications of the constructed models are lie in study of different induction systems for heating samples of different shapes. The developed methods and approaches can be applied to other electrical engineering processes. The proposed solutions allow to efficiently use the results obtained for steel rings, disks, gears, shafts, springs and other symmetrical workpieces of different types and sizes, for constructing induction systems and for parametric search of optimal system configurations.

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Received 20.01.2019, accepted 15.04.2019.

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Статья поступила в редакцию 20.01.2019, принята к публикации 15.04.2019.

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