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Selected Issues of Energy-Efficient Induction Heating of Railway Rail

Abstract. *The article presents selected issues related to energy-efficient induction heating of a railway rail. The heater proposed by the authors is powered from the inwerter. In the induction heating system existing railway automation can be used. The article contains the results of simulation and experimental investigations of ferromagnetic properties of the rail in terms of the effectiveness of induction heating, the shape of the heater and its location on the rail during induction heating. The choosen results of the heating efficiency tests.of the induction rail are also presented.*

Streszczenie. *Artykuł przedstawia wybrane zagadnienia związane z ogrzewaniem indukcyjnym szyny kolejowej. Zaproponowany wzbudnik grzejący szynę jest zasilany z falownika. Artykuł zawiera wyniki badań symulacyjnych i eksperymentalnych ferromagnetycznych właściwości szyny w aspekcie oceny skuteczności zastosowania grzania indukcyjnego oraz kształtu wzbudnika i jego lokalizacji na szynie podczas grzania.* ***Wybrane zagadnienia energooszczędnego ogrzewania indukcyjnego rozjazdów kolejowych***

Keywords: induction heating of a railway rail, properties of rail, inductor.
Słowa kluczowe: ogrzewanie indukcyjne, rozjazdy kolejowe

Introduction

Railway turnouts are part of railways used to change the direction of travel of a rail vehicle from the main track to another track (branch) or vice versa. They are key elements of railways which are exposed to negative weather conditions such as snowfall, snow drifts, low temperature or sleet. Disadvantageous winter conditions may block turnouts and cause problems with traffic operation. Effective protection assures good performance of turnouts and contributes to efficiency and safety of rail traffic.

Currently the most common heating system for railway turnouts in Europe is electric resistance heating system (eor) (Fig.1).

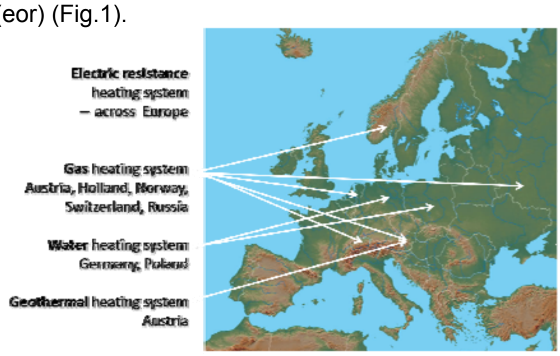

Fig.1. Heating systems of rail turnouts

Providing a power of 330W per running meter of the rail in the eor method gives good effectiveness of heating rail turnouts during the heating period. Under average atmospheric conditions (i.e. at temperature down to -20°C) with average snowfall with currently used 330W/m heaters eor efficiency ensures correct operation of heated turnouts. The efficiency of heating turnouts means the ability of heating systems to be removed from all critical elements of snow switches and icing in a sufficiently short time. At the same time the energy consumed for this purpose should not be excessively large. Many factors influence the heating efficiency such as: ambient temperature, the intensity of snowfall, the intensity of snow blowing by wind and passing trains, speed, number and length of passing trains, wind speed, air humidity, installed heating power per 1 mb of rail, the cross-section and shape of the radiator and its arrangement on the rail, quantity and quality of the holders fixing the radiators, efficiency of separation transformers, weight of rails, turnout construction, dehydration of the turnout, etc.

A typical diagram of electric resistance heating system of rail turnout is shown in Figure 2. It employs electric heaters of power between 300-350W/m and the supply voltage of 230V AC.

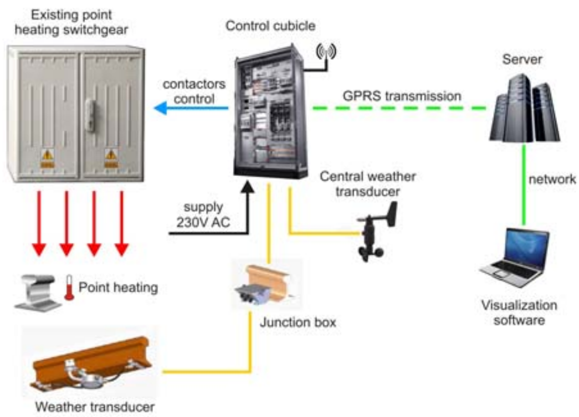

Fig.2 Electric resistance heating system of rail turnout

Resistance heating has several disadvantages:

- low energy efficiency (high temperatures – about 200C of the heater produce only a dozen degrees of temperatures in the rail head)
- short life of heaters
- drying of greases under the influence of great heater.temperature

It causes high costs of: operation, maintenance and electricity consumption. This kind of heating results in maximal increase of temperature in the heater.

The idea of rail induction heating is not completely new: Polish Railways PKP tried to heat turnouts with a variable magnetic field at a frequency of 50Hz in the 1970s. The heating copper rods.located on a rail.were powered by AC low voltage causing a high current of 50Hz with the help of transformer. This current induced a large alternating magnetic field closed by the rail. Eddy currents induced by this field.heated the rail.

Advantages over resistance heating were following:

- lower electricity consumption.(35%)
- lower operation and maintenace costs

- more effective removal of snow and.ice as a rail heats more quickly
- low safe voltage
- lower temperatures of the heater (about 65^{o}C)
- longer life of an induction heater (inductor)
- slower drying of greases

They demonstrated lower electricity consumption, operation and maintenance costs.in case of induction heating. Unfortunately.the level of technology.didn't guarantee reliable operation of the system.and effectively blocked the solution. In today's era of new technologies.you can return to that already forgotten concept and try to develop it further.

The aim of the paper is to present the results of tests determining the possibilities of using induction heating in railway turnouts where you can use existing rail automatics shown in Figure 2 and insert the inductor heater in place of resistance heater („point heating"). There is lack of data which would characterize electromagnetic properties of the rail as a part of the induction heating system at variable frequencies of the supply voltage. The theoretical simulation and experimental analysis of the structural, electric and magnetic properties of selected types of rail has been made [11,12]. They are the starting point for appropriate selection of an inductor and its placement on the rail and supply power generator so that performance and safety of rail traffic can be obtained with high energy efficiency (Fig.3).

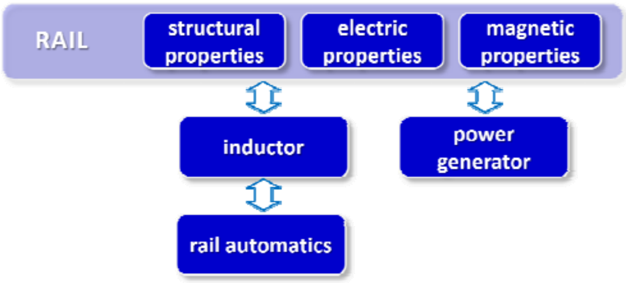

Fig.3. Concept of an energy-efficient induction heating system of railway turnouts

Structural properties of rail

Testing of selected types of rail have been concentrated on the rail type 60E1which is a part of high-speed turnouts existing in Europe. Totally 21 samples taken from different locations of rail shown in Figure 4 have been analysed and tested [11] in terms of the structure's impact on the ferromagnetic properties of the rail.

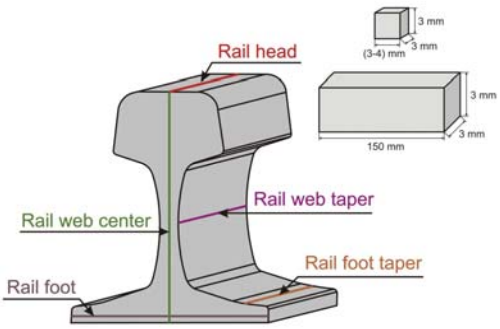

Fig.4 Locations of 60E1 rail testing samples

X-ray diffraction testing by a Scanning Electron Microscope were used to determine structural properties of all the tested samples [5,12].

The results of the sample tests showed that the location of the sample is important since 3 parts of the rail (head, web and foot) have different properties pre-determined by their microstructure (Fig.5).

Fig. 5 Microstructure of rail steel [12]

The magnetic properties of rail steel are influenced by:
- chemical composition of steel,
- phase composition,
- conditions of heat and plastic treatment,
- the degree of fragmentation of the structure.

The chemical composition of the steel determines the type of phases forming in the material, their stability and participation of the ferritic phase in the material structure. During the heat and plastic processing of the steel, phase transitions take place in the material. The heating of ferritic steel at a higher temperature of 727 ° C converts ferrite to paramagnetic. The magnetic properties of steel are also affected by the degree of fragmentation of the crystal structure. The greater the degree of fragmentation of the crystal structure of the material, the greater the coercivity is characterized by the ferromagnetic material.

Experimental results confirmed percentage admixtures of magnetic and non-magnetic materials which have relatively high impact on electric and magnetic quantities of the rail.

They indicated that the rail was ferromagnetic polycrystalline material with a different structure. Ferromagnetic properties of rail allow the use of induction heating technology.

Introduction to induction heating method

The use of the phenomenon of rail induction heating requires precise knowledge of the properties of the electromagnetic field in the rail and its surroundings [3,11]. The electromagnetic fields **E** and **H** that are produced by the high-frequency electric current in a ferromagnetic environment can be represented using Maxwell's equations:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

where: **H** - magnetic field intensity vector [A/m]; **J** - electric current density vector [A/m^2]; **D** - electric flux density [C/m^2]; **E** - electric field intensity vector [V/m]; **B** - magnetic induction vector [T] ; t - time [s]

Penetration depth of the electromagnetic wave u in the rail is connected with rail magnetic permeability μ and can be expresed [3]:

$$u = \sqrt{\frac{2 \cdot \rho}{\omega \mu \cdot \mu_0}} \tag{3}$$

$$\omega = 2\pi \cdot f \tag{4}$$

where: u - penetration depth of the electromagnetic wave [m]; ω - pulsation [rad/s]; μ - relative magnetic permeability μ_0 - vacuum permability, μ_0 = 4π·10^{-7} [Wb/m]

Rail magnetic permeability μ depends on many factors: the contact stresses in the rail surface, elasticity of steel, magnetic field intensity, frequency and temperature and so on and it cannot be easily determined.

Heating power of a volume unit P_V during induction heating in rail is [3]:

$$P_V = \frac{\rho \cdot H_m^2}{u^2} e^{-\frac{2x}{u}} \tag{5}$$

where: P_V - heating power of a volume unit [W/m^3]; ρ - electric resistivity [Ωm]; f - frequency [Hz]; x - distance from the surface of the rail [m]; H_m - amplitude of the magnetic field intensity [A/m]

Heating power of a volume unit P_V should be as large as possible to ensure high heating efficiency and depends on the frequency f of the supply voltage for a known amplitude of the magnetic field intensity H_m.

Electric and magnetic properties of rail

As mathematical model of induction heating of a rail – ferromagnetic material of heterogeneous structure is complicated, experimental analysis of the electric and magnetic properties of selected types of rail has been made. Tab.1 summarizes electric and magnetic properties of the rail and suitable measuring methods that have been practically utilized [11].

Table.1 electric and magnetic properties of the rail

Electric and magnetic rail properties (quantities)	Measuring methods
Electric resistivity ρ	Four-point linear probe
Initial magnetic permeability $\mu_{initial}$	Precise RLC bridge
Magnetic permeability $\mu = f_\mu(H)$ Maximum magnetic permeability μ_{max}	Fluxmetre
Prime magnetization curve $B = f_B(H)$	Fluxmetre
Intensity of coercivity field H_c	Coercion metre
Magnetization curve $M = f_M(H)$ Saturation M_s	Physical Property Measurement System

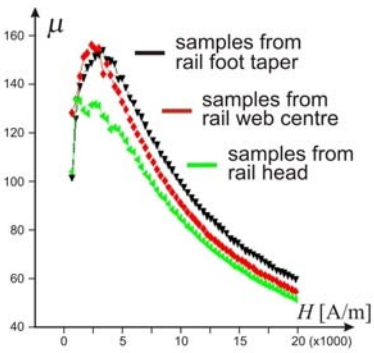

Fig.6 Relative magnetic permeability $\mu = f_\mu(H)$

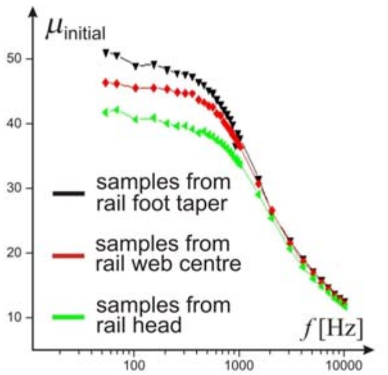

Fig.7. Initial relative magnetic permeability $\mu_{initial} = f_{\mu initial}(f)$

Figures 6-9 present the experimental results obtained with the help of measurement methods presented in Table 1. Quantities that are shown in Figures 6-9 were tested from different parts of the rail.

Relative permeability μ (Fig.6) and initial relative permeability $\mu_{initial}$ (Fig.7) reach maximum values in the rail foot taper (black colour). The higher is value of rail permabilities the higher is effectiveness of heating.

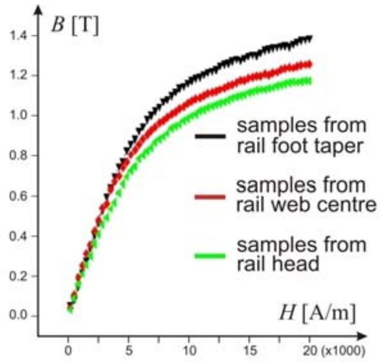

Fig.8 Prime magnetization curves $B = f_B(H)$

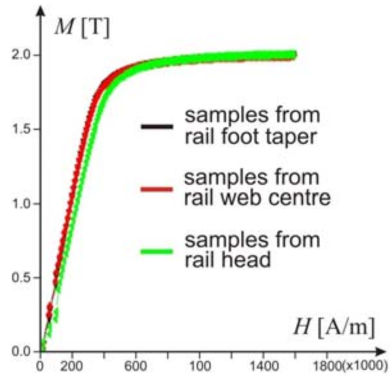

Fig.9. Magnetization curves $M = f_M(H)$

Results of experimental testing (Fig. 8) indicate that the rail foot taper has the best magnetic properties of all parts of the rail which is illustrated with the black curve. The higher values of induction indicate the stronger magnetic field and the higher effectiveness of heating. Magnetization curves (Fig. 9) have similar values in the whole volume of the rail.

Presented measuring results indicate that the rail foot taper provides the best conditions for induction heating in the rail.

Simulation testing of rail induction heating

To analyse rail induction heating by simulation tesing the Finite Element Method Magnetics software (FEMM) has been used (Fig.10). Advantage of FEMM is that the impact of an electromagnetic field generated by eddy currents across a rail is taken into consideration.

For purposes of the testing in FEMM a simulation model of induction heated rail has been defined under following assumptions:

- effect of an electromagnetic field generated by eddy currents across a rail is taken into consideration,
- frequency of the supply voltage f (50 ÷ 1000)Hz,
- constant current density in the heating cable,
- electric and magnetic properties taken into account: resistivity ρ, prime magnetization curve $B = f_B(H)$, intensity of coercivity field H_c,
- description of the magnetic field by means of vector potential **A**,

- zero Dirichlet boundary conditions – setting of vector potential equal to zero (**A** = 0) along a selected boundary.

The magnetic model developed in Flux3D provides for observation of electric and magnetic effects in the rail's internal structure triggered by flow of eddy currents. The model is utilised to determine the depth of magnetic field penetration into the rail structure as dependent on variations of magnetising current frequency and will serve to determine a temperature distribution along the rail in the process of heating. Knowledge of this temperature distribution or, to be more exact, of maximum temperature values attained by the individual rail sections is the key to success of this research.

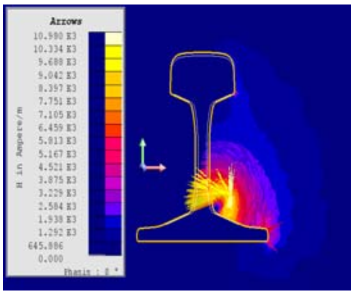

Fig.10. Graphic interpretation of the magnetic field intensity *H* distribution during rail induction heating in FEMM [11]

In the simulation process the influence of the inductor's placement on distribution of magnetic field intensity *H* has been tested (Fig. 11).

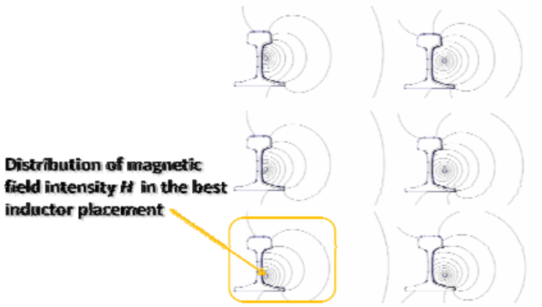

Fig.11. Influence of the inductor's placement on distribution of magnetic field intensity *H*

Figure 11 shows distribution of magnetic field intensity in the best inductor placement. There is minimum air gap between the inductor and the rail and there is minimum magnetic field leakage. For these reasons the inductor should be positioned on the rail foot.

The air gap must be fully eliminated in continuing research and if this is not possible, the gap needs to be minimised in order to reduce magnetic field dispersion as much as practicable.

Experimental results

In the case of rail induction heating with inductor as a flat oblong heater (design of an inductor is similar to the heater used in resistance turnout heating) induction *B* increases and depth of magnetic field penetration into the rail *u* is reduced when frequency rises. Unfortunately most of the magnetic field lines run in the air and distribution of magnetic field is heterogeneous along the rail foot taper. The efficiency of induction heating with the applied inductor is very low [5].

To create a closed magnetic circuit between the inductor and the rail foot the shape of inductor has been modified (Fig.12) [9]. Closed magnetic circuit focuses the magnetic field in the rail. The magnetic field leakage is minimized.

Fig. 13 presents thermal images of heated rail with the new inductor. Increase of temperature ΔT in the frequency range f (350÷850) Hz of the supply voltage demonstrates maximum efficiency of the rail induction heating with the coil shaped inductor in the test frequency range of up to 1 kHz. The rail's temperature grows by 21^{o}C with a minimum heating (5^{o}C) of the inductor's core during 30min of heating. The temperature rise of rail reaches maximum for *f* =650Hz in the test frequency range.

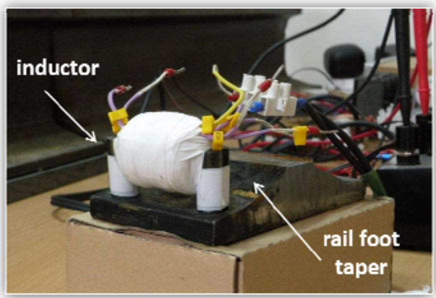

Fig. 12. The coil shaped inductor with a ferrite ore (prototype)

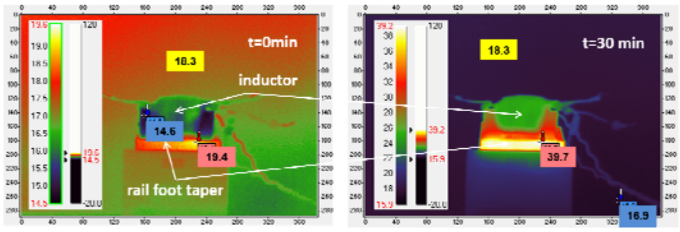

Fig.13. Thermal images of heated rail foot with the coil shaped inductor (number of coils *z*=150, *f* =*650*Hz, *P* = 10W, 30 min of heating)

Conclusions

In simulation and experimental studies of the rail induction heating, the highest energy efficiency was obtained within the rail foot using a coil shaped coil wound on a ferrite core [9]. The tested inductor can be a part of induction heating system of rail turnouts. It is powered from an inverter where gate pulses are generated by a control system based on assessments of weather conditions and snow cover of a turnout. Existing rail automatics used in resistance heating system can be used in the induction heating system.

Presented solution has a potential to bring benefits in several areas if compared with other commonly used electric heating systems: higher energy efficiency, lower operation and maintenance costs, comparable production costs. Authors are planned to continue research and result in implementation of induction heating on the railway turnouts.

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