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Inductive heating and quenching of planetary shafts

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Manufacturing and processing

ABSTRACT

Purpose: High mechanical and temperature cyclic loading of the final products for automotive, construction, transport and agriculture mechanization industry, demands sufficient mechanical properties of all of their components during its exploitation. Majority of the components is made from steel, by different cold forming processes. Their main demanded characteristics are surface wear resistance and fatigue strength under pulsating stress in combination with cyclic temperature loading, which could be achieved only by appropriate heat treatment.

Design/methodology/approach: In the experimental part of our work, the efficiency of the combined inductive heating and water quenching heat treatment and quality of the planetary shafts were analyzed, with the use of thermographic analysis, hardness measurements, and metallographic examination.

Findings: Combination of inductive heating and water quenching is the most effective heat treatment process of carbon steel planetary shafts for the diesel engine starters.

Research limitations/implications: Long life span of carbon steel planetary shafts it's essential for their economical production. The replacement of starter is expensive from both: money and working time point of view.

Practical implications: Surface temperature measurements during the inductive heating process were realized in the industrial environment. The intensity and homogeneity of the planetary shaft surface temperature field was measured by thermographic camera.

Originality/value: On the base of theoretical knowledge and measurements, a mathematical model for temperature conditions determination in the shaft during the entire process of heating and quenching was carried out. On the basis of developed mathematical model a computer program was worked out, and used for analyses and optimization of planetary shafts induction hardening process.

Keywords: Heat treatment; Carbon steel; Planetary shaft; Inductive heating; Quenching

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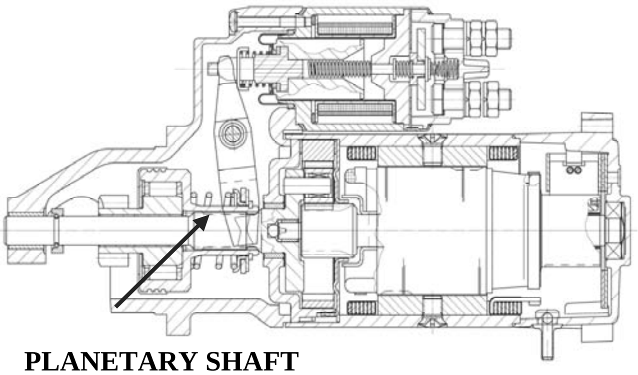
1. Introduction

Slovenian company ISKRA Avtoelektrika d.d. is one of the largest European producers of electrical components and equipment for automotive, construction, transport and agriculture mechanization industry. High mechanical and temperature cyclic loading of the final product, during its exploitation, demands sufficient mechanical properties of all of its components.

Majority of the components is made from steel, by different cold forming processes [1]. Their main demanded characteristics are surface wear resistance and fatigue strength under pulsating stress in combination with cyclic temperature loading, which could be achieved only by appropriate heat treatment [2-4]. Combination of inductive heating and water quenching is the most effective heat treatment process [5-9] of carbon steel planetary shafts for the diesel engine starters (Figure 1).



PLANETARY SHAFT

Fig. 1. Starter of a diesel engine with planetary shaft. Dimensions of the shaft are: ∅14 mm × 155 mm

2. Materials

The planetary shaft is made from the well known CK 45 steel (material number 1.1191 according to DIN designation) [10], which is one of the most applied materials for this kind of mechanical parts. The chemical composition of the steel is given in the Table 1.

Table 1.
Chemical composition of CK 45 steel [10]

Element	Standard (mass. %)	Measurements (mass. %)
C	0.47 – 0.50	0.48
Si	≤ 0.40	0.24
Mn	0.70 – 0.80	0.71
P	≤ 0.035	0.020
S	0.02 – 0.04	0.026
Cr	0.17 – 0.25	0.17
Mo	≤ 0.10	0.009
Ni	≤ 0.40	0.004
(Cr+Mo+Ni)	≤ 0.63	0.183

3. Device description

The inductive spin-hardening device 3KTC (100 kW; 100 kHz) (Figure 2), which is used in Slovenian company ISKRA Avtoelektrika d.d. for induction spin-hardening thermal treatment of different mechanical parts and components was made by Italian company SAET from Turin. Device is designed for spin case-hardening treatment of cylindrical shape products from 12 to 32 mm in diameter and 100 to 500 mm length.

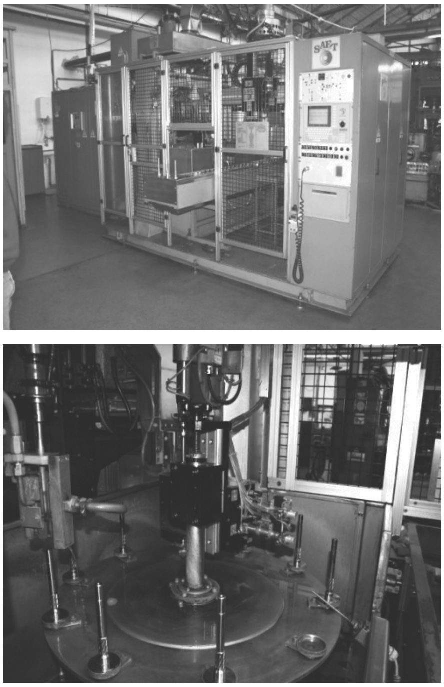


Fig. 2. The spin case-hardening device 3KTC (above). Inductor and manipulation system detail (below)

Heat treatment and device parameters are collected in Table 2.

Table 2.
Processing and device parameters

Parameter	
Theoretical power (kW)	93
Actual power (kW)	72.8
Frequency (kHz)	83
Voltage (V)	508
Heating time (s)	2.5
Quenching time (s)	1.5
Total time of the cycle (s)	15

4. Temperature measurements

During induction heat treatment process the planetary shaft turns around its axis, which ensures uniform heating all over the surface and through the cross section.

Temperature of the surface changes extremely rapidly between room temperature and 1120°C. Rotational speed is approximately 10 rev/sec. Optimal heating time for required planetary shaft properties is 2.5 seconds, followed by 1.5 second quenching period with oil-water emulsion. After that, planetary shaft is ejected from manipulating system and cooled down in surrounding air.

For planetary shaft surface temperature determination we used thermographic camera ThermaCAM PM675 FLIR System (Figure 3). Our measurements were made in cooperation with TERMING d.d. company from Ljubljana.

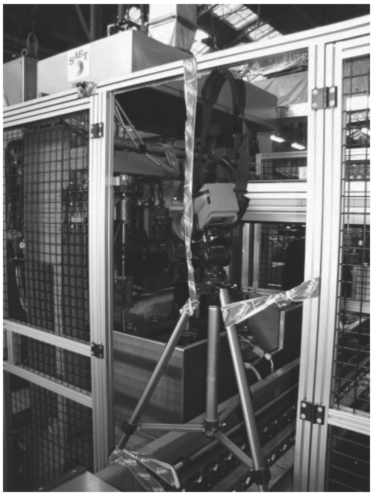


Fig. 3. Thermographic camera ThermaCAM PM675

Because automatic predetermination of emissivity in thermographic camera as thermal black body (ε=1), real emissivity value must be determined before temperature measurements. As is well known, emissivity is dependent upon material, surface condition and temperature [11, 12]. According to literature data for CK 45 steel, emissivity value varies between 0.6 and 0.9, depending upon temperature and surface conditions [13]. In our case of induction heating process, surface temperature varies between room temperature and 1120°C. Furthermore, quality of surface changes from polished to heavily oxidized, which has significant influence on emissivity value. Because induction heating is a very fast process, we had to determine emissivity as engineering correct constant for the whole temperature range and surface mutation. Chronological review of induction case-hardening process.

For determination of real value of emissivity, we made comparative temperature measurements with Isotech T.T.I.-7 thermograph and thermographic camera of the same planetary shaft, heated in electro-resistance furnace. Best fitting emissivity value for thermographic camera was approximately 0.7.

Several thermographic snapshots (Figure 4) were recorded at regular intervals of induction heating (entire heating time is approximately 2.5 sec.) Thermographic recording (Figure 5a) is showing temperature profile on a surface of planetary shaft after 0.5 second and thermographic recording (Figure 5b) after 2.5 second of induction heating. Maximum measured temperature on bevel gear surface was 1120°C.

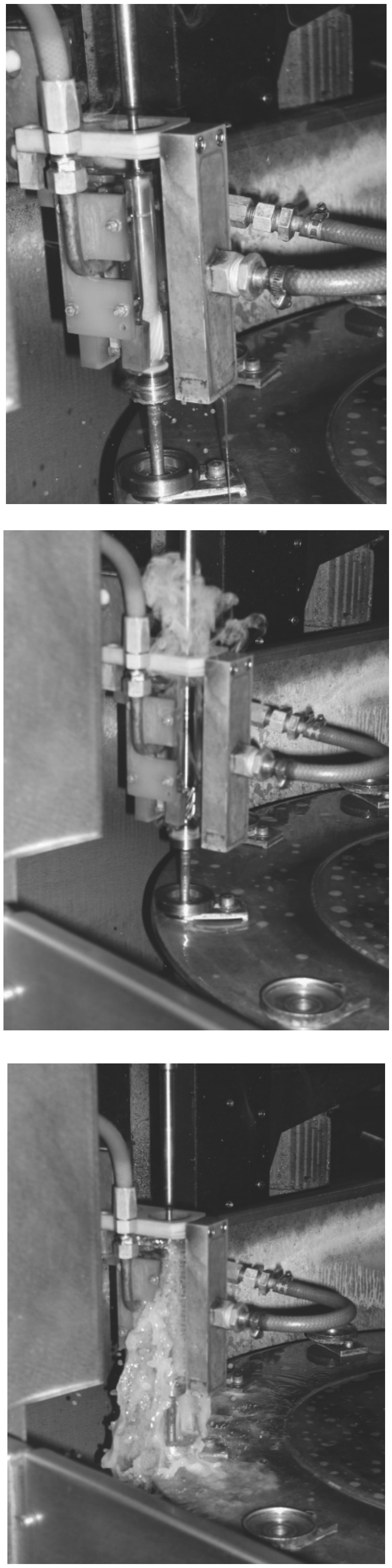
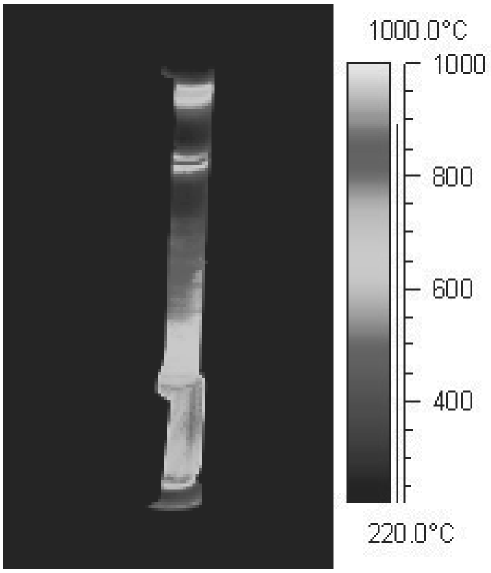


Fig. 4. Chronological review of induction case-hardening process

a)



b)

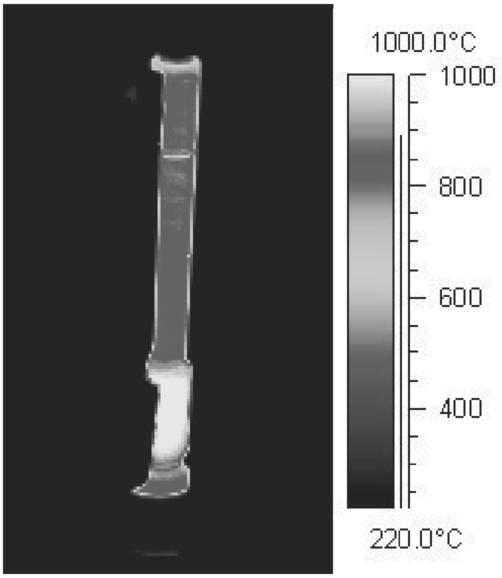


Fig. 5. Thermograph records: a) At the beginning of induction heating (0.5 sec). b At the)end of induction heating (2.5 sec)

5. Mathematical model

Primary task of our work was to develop a mathematical model for thermal field calculation inside the planetary shaft during inductive heating and quenching, which would enable examination of temperature distribution at any time of induction heat treatment [14, 15]. Mathematical model is based upon different assumptions and boundary conditions:

- planetary shaft is approximated as constant cross section cylinder
- material of the shaft is homogeneous and isotropic
- starting temperature field in the shaft is homogeneous and equal to the of the surrounding temperature
- mathematical model doesn't consider released or consumed latent heat at the allotropic phase changes
- because of ″skin effect″ phenomenon at the inductive heating, temperature at 0.2 mm below the surface has the same temperature as surface
- surface temperature during induction heating is determined with thermographic camera measurements
- during induction heating period, surface temperature rises between separate intervals monotonically to the measured temperatures for those particular intervals
- average heat transfer coefficient in quenching period with oil-water emulsion is determined backwards, after microstructure observations of trial precursors
- thermal properties are temperature dependant
- density is assumed as a constant during entire induction spin case-hardening process.

Temperature field in any solid body is monotonous function of time and space. For temperature distribution calculation inside planetary shaft we used cylindrical coordinate system. General form of heat conduction equation in cylindrical coordinate system in three dimensional (3D) forms is given by:

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{1}{r^2}\cdot\frac{\partial}{\partial\varphi}\cdot(\lambda\cdot\frac{\partial T}{\partial\varphi})+ \qquad (1)$$

$$+\frac{\partial}{\partial z}\cdot(\lambda\cdot\frac{\partial T}{\partial z})+q^{'''}=\rho\cdot c\cdot\frac{\partial T}{\partial t}$$

where:
r, φ ,z ………. cylindrical coordinate system [m; rad; m]
T …………… temperature [K]
$\rho = \rho(T)$ ……. density [kg/m^3]
$\lambda = \lambda(T)$…….. thermal conductivity [W/(m·K)]
$c = c(T)$ ….. .. specific heat [J/(kg·K)]
$q^{'''}$ …………... volumetric heat generation rate [W/m^3]

Because planetary shaft turns around its axis during entire induction spin case-hardening process, surface temperature is homogenous ($\frac{\partial T}{\partial\varphi}=0$), and we could make an assumption of two-dimensional (2D) transient heat transfer. Assuming 2D transient heat transfer with variable thermal properties and no internal heat generation or consumption, general partial differential equation reduces to:

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}\cdot(\lambda\cdot\frac{\partial T}{\partial z})=\rho\cdot c\cdot\frac{\partial T}{\partial t} \qquad (2)$$

For calculation of temperature distribution inside planetary shaft we used explicit finite difference method (FDM), where thermal properties (thermal conductivity, specific heat) at given temperature are calculated for every time step with Lagrange interpolation [16].

6. Results

Figure 6 shows numerical results of temperature distribution through the cross-section 5 mm beneath upper groove (see Figure 8) for the case of induction heating (2.5 second) and quenching (1.5 second) with water-emulsion. Average heat transfer coefficient in quenching period was determined on the basis of microstructure observation of trial precursors. Best fit value of heat transfer coefficient was htc = 35000 W/m^{2}K.

Figure 7 shows photographs of heat treated planetary shaft (left) and its longitudinal cross-section with clearly visible hardened case (right). Thickness of the hardened case is approximately 1.4 mm. Cutting was made with the water jet cutting machine.

In Figure 8 is shown graphical course of the HV5 hardness, according to the Vickers method, from the surface over the quenched layer to the core of the planetary shaft treated at standard conditions.
Microstructures at different depths underneath the surface on cross section line are presented in Figure 9. Surface of the shaft is completely martensitic (A). At depth 0.7 mm under the surface, microstructure (B) is composed from martensite and ferrite, which was not completely transformed into austenite during induction heating period.

Thickness of hardened case is approximately 1.4 mm (C), where constituents of microstructure are martensite, pearlite and ferrite. Beneath that depth microstructure is composed from pearlite and ferrite.

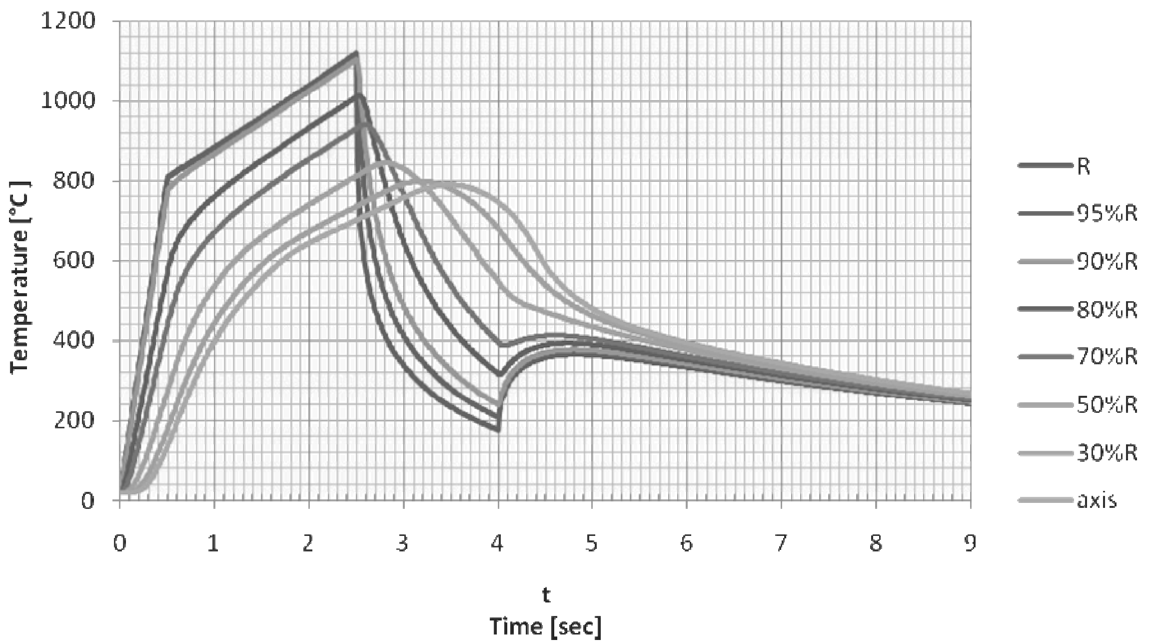


Fig. 6. Calculated temperature field in planetary shaft during induction hardening process (htc = 35000 W/m^{2}K)

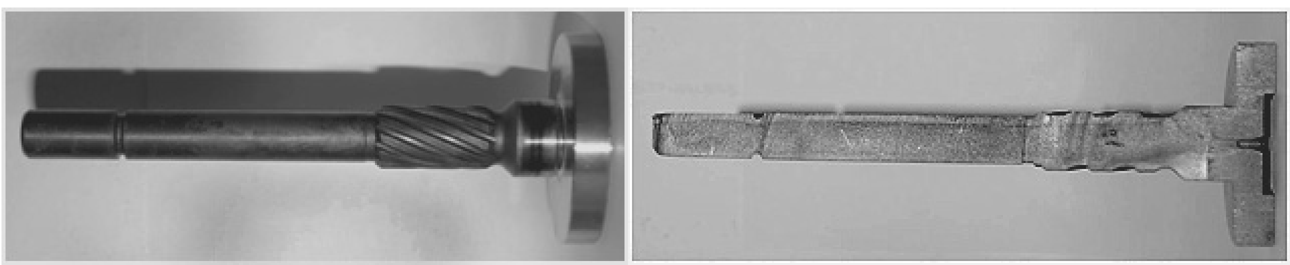


Fig. 7. Heat treated shaft (left). Longitudinal cross-section of the planetary shaft (right). Cutting was made with water jet cutting machine. Thickness of hardened case is approximately 1.4 mm

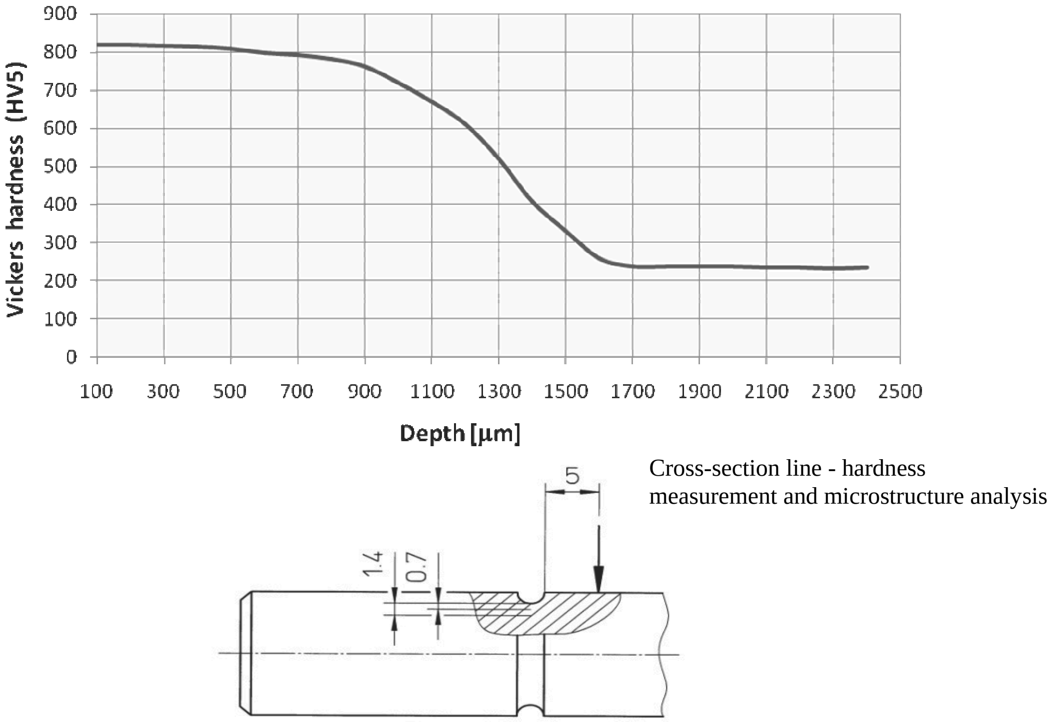


Fig. 8. Hardness course measured over the hardened case of the planetary shaft (above) and cross section line (below)

a)
b)
c)
d)

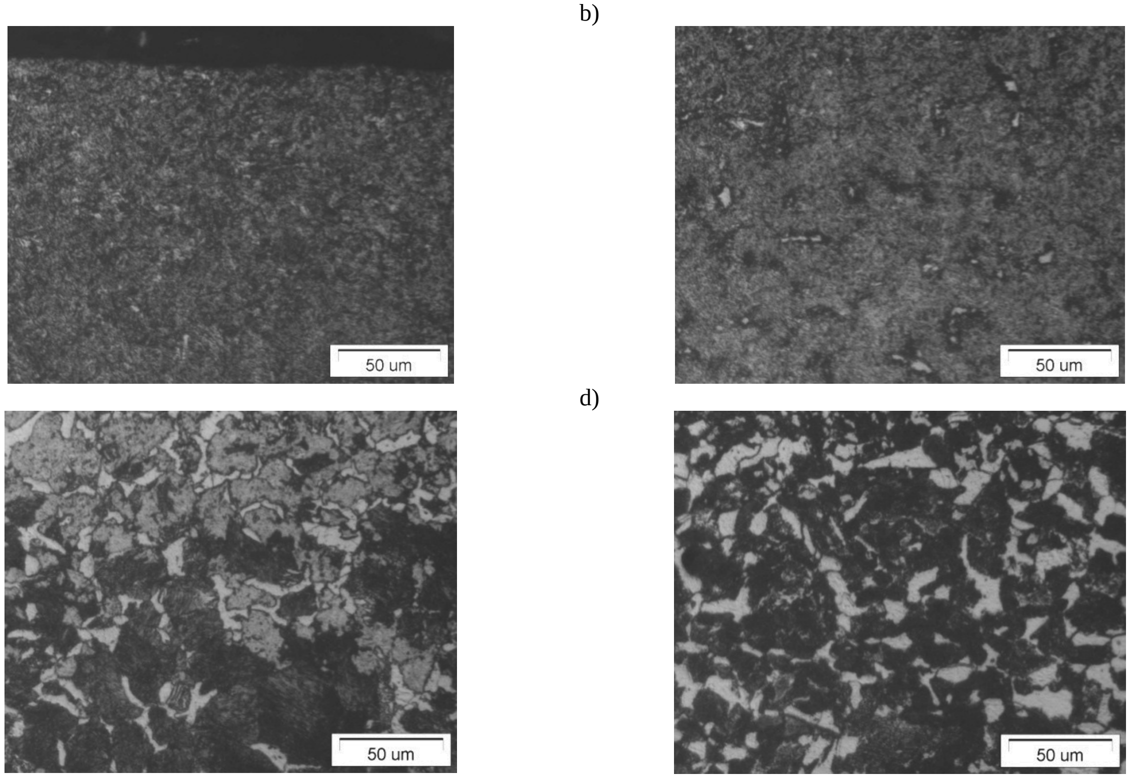


Fig. 9. Steel microstructures at different depths under the surface: a) surface; b) 0.7 mm; c) 1.4 mm;d) 2.1 mm

7. Conclusions

In our research work, we analyzed induction spin hardening process of carbon steel planetary shafts for diesel engine starters.

Surface temperature thermographic camera measurements of planetary shaft during induction spin-heating period were carried out in industrial environment of Slovenian company Iskra Avtoelektrika d.d. For accurate temperature measurement with thermographic camera, we made comparative temperature measurements with thermograph and thermographic camera of the same planetary shaft, heated in electro-resistant furnace. Best fit emissivity value for thermographic camera was 0.7.

On the basis of our mathematical model we developed a computer program for temperature distribution calculation inside planetary shaft. Boundary condition for numerical calculations (htc = 35000W/m^{2}K) was determined backwards, after microstructure observation of test precursors.

On the basis of the numerical results we optimized heating and quenching time for induction hardening process of planetary shaft.

Induction spin hardened planetary shaft was substantially deformed during water jet cutting. Therefore next reasonable step would be calculation of stress-strain state in planetary shaft.

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