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Original article

Inductive Heating and Quenching of Planetary Shafts for Diesel Engine Starters

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ABSTRACT

High mechanical and temperature cyclic loading of the final products for automotive, transport, construction and agriculture mechanization industry, demands sufficient mechanical properties of all of their components during its exploitation. Majority of the components is made of 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. 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. Combination of inductive heating and water quenching is the most effective heat treatment process of carbon steel planetary shafts for the diesel engine starters. 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. Surface temperature measurements during the inductive heating process were performed in the industrial environment. The intensity and homogeneity of the planetary shaft surface temperature field was measured by thermographic camera. 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, and used for analyses and optimization of planetary shafts induction hardening process.

Key words: *Planetary Shaft, Carbon Steel, Heat Treatment, Inductive Heating, Quenching, Temperature.*

1. INTRODUCTION

Company MAHLE Electric Drivers Slovenia d.o.o., located in Šempeter near Gorica, stands as one of the major European manufacturers of electrical components and equipment tailored for the automotive, construction, transportation, and agricultural mechanization industries. The final product endures high levels of mechanical and temperature cyclic loading throughout its usage, necessitating adequate mechanical properties across all its components for optimal performance and longevity.

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The majority of the components manufactured by the company are produced from steel, employing various cold forming processes [1]. The primary sought-after attributes for these components encompass surface wear resistance and fatigue strength, particularly under pulsating stress alongside cyclic temperature loading. Achieving these specific characteristics necessitates suitable heat treatment methodologies [2, 3]. Among the various approaches, the most effective heat treatment process identified for carbon steel planetary shafts used in diesel engine starters (as depicted in Fig. 1) involves a combination of inductive heating and water quenching [4-7]. This method has proven to be highly efficient in meeting the desired properties required for these components.

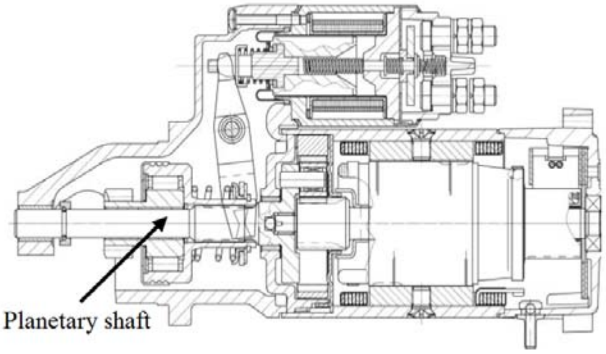

Fig. 1 Diesel engine starter with planetary shaft (Φ14 mm x 155 mm)

2. EXPERIMENTAL WORK

The inductive spin-hardening device, 3KTC (100 kW; 100 kHz) (refer to Fig. 2), is employed by MAHLE Electric Drivers Slovenia d.o.o. for conducting induction spin-hardening thermal treatments on various mechanical parts and components. This equipment, manufactured by the Italian company SAET based in Turin, is specifically engineered for spin case-hardening treatments on cylindrical-shaped products ranging from 12 to 32 mm in diameter and 100 to 500 mm in length.
Heat treatment and device parameters are collected in Table 2.

Table 1. Processing and device parameters

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

During the induction heat treatment process, the planetary shaft rotates around its axis, facilitating uniform heating across the entire surface and throughout the cross-section of the shaft. The surface temperature undergoes rapid changes, ranging from room temperature to 1120°C. The rotational speed is approximately 10 revolutions per second. The optimal heating duration necessary to achieve the desired properties of the planetary shaft is 2.5 seconds, followed by a 1.5-second quenching phase using an oil-water emulsion (as shown in Fig. 3). Subsequently, the planetary shaft is removed from the manipulation system and allowed to cool down in the surrounding air.
To determine the surface temperature of the planetary shaft, we utilized a thermographic camera, specifically the ThermaCAM PM675 from FLIR Systems. These measurements were conducted in collaboration with TERMING d.d., a company based in Ljubljana.

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

Determining the real emissivity value becomes essential for accurate temperature measurements since thermographic cameras automatically presume emissivity as that of a thermal black body (ε = 1). Emissivity, a factor dependent on material, surface condition, and temperature [9,10], is crucial for precise readings. For CK 45 steel, literature indicates emissivity values ranging between 0.6 and 0.9, influenced by temperature and surface conditions [11]. In our case, involving induction heating with surface temperatures ranging from room temperature to 1120°C, the surface quality transitions from polished to heavily oxidized. This variation

significantly impacts the emissivity value. Due to the rapid nature of induction heating, we established a single, engineering-correct constant for emissivity across the entire temperature range and surface mutations to ensure accuracy in our measurements.
To ascertain the actual emissivity value, we conducted comparative temperature measurements using both the Isotech T.T.I.-7 thermograph and the thermographic camera on the same planetary shaft. This shaft was heated in an electro-resistance furnace. Through these comparative measurements, we determined that the most suitable emissivity value for the thermographic camera was approximately 0.7, resulting in the best fit for the obtained temperature measurements.

Figure 3. Chronological review of induction case-hardening process

Several thermographic snapshots were captured at consistent intervals throughout the induction heating process, which spans approximately 2.5 seconds in total. The thermographic recording depicted in Fig. 4 (above) displays the temperature profile on the surface of the planetary shaft after 0.5 seconds of induction heating. Additionally, Fig. 4 (below) showcases the thermographic recording following 2.5 seconds of induction heating. The maximum recorded temperature observed on the bevel gear surface reached 1120°C. These recordings offer a visual representation of the temperature evolution during different stages of the induction heating.

3 MATHEMATICAL MODEL

The primary objective of our work involved the development of a mathematical model to compute the thermal field within the planetary shaft throughout the processes of inductive heating and quenching. This model aimed to facilitate the analysis of temperature distribution at any given time during the induction heat treatment [12]. The mathematical model relied on ten distinct assumptions and boundary conditions, serving as the foundational elements for its formulation and accurate representation of the thermal dynamics within the shaft.

- The planetary shaft is modeled as a cylinder with a constant cross-section.
- The material properties of the shaft are assumed to be homogeneous and isotropic.
- The initial temperature distribution within the shaft is uniform and matches the ambient temperature.

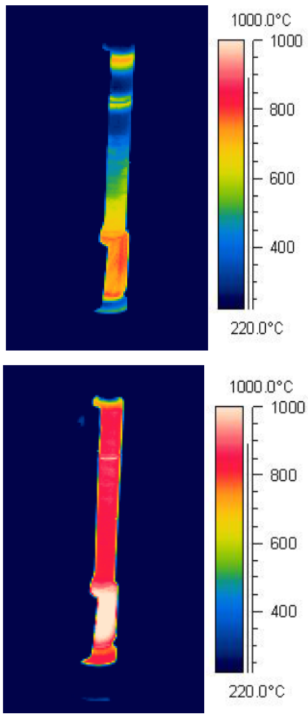

Fig.8 Thermograph records:

Above: at the onset of induction heating (0.5 seconds)
Below: at the end of induction heating (2.5 seconds)

- The model does not account for any heat released or absorbed during allotropic phase changes.
- Thermal properties are considered to vary with temperature.

- Density is assumed to remain constant throughout the entire process of induction spin case-hardening.
- Surface temperatures during induction heating are determined through measurements obtained from a thermographic camera.
- Due to the "skin effect" phenomenon during inductive heating, temperatures at 0.2 mm beneath the surface are assumed to match the surface temperature.
- During the induction heating period, surface temperatures progressively increase between separate intervals in a monotonic manner, reaching the measured temperatures for those specific intervals.
- The average heat transfer coefficient during the quenching phase involving oil-water emulsion is retroactively determined following observations of microstructural changes in trial samples.

Temperature field in any solid body is monotonous function of location and time. 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:

$$\frac{1}{r}\left(\lambda\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial r}\left(\lambda\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\varphi}\left(\lambda\frac{\partial T}{\partial\varphi}\right)+ +\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+q''' = \rho\cdot c\cdot\frac{\partial T}{\partial t} \quad (1)$$

where:

r, φ, z	cylindrical coordinate system [m; rad; m]
T	temperature [K]
ρ= ρ(T)	density [kg/m3]
λ= λ(T)	thermal conductivity [W/(m K)]
c = c(T)	specific heat [J/(kg K)]
q'''	volumetric heat generation rate [W/m^3]

Under the assumption of a homogeneous surface temperature ($\partial T/\partial\varphi = 0$)due to the rotation of the planetary shaft throughout the induction spin case-hardening process, and considering a scenario of two-dimensional (2D) transient heat transfer, assuming variable thermal properties and no internal heat generation or consumption, the general partial differential equation for heat transfer can be simplified.

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

To calculate the temperature distribution within the planetary shaft, we employed the explicit finite difference method (FDM). Within this method, we dynamically computed thermal properties (such as thermal conductivity and specific heat) at each temperature for every time step using Lagrange interpolation. This approach allowed us to capture the evolving thermal behavior and properties of the material as temperature changes during the process.

4 RESULTS AND DISCUSSION

Fig. 5 displays the numerical outcomes illustrating the temperature distribution within the cross-section located 5 mm beneath the upper groove (refer to Fig. 8). These results are derived from simulations conducted during the induction heating period lasting 2.5 seconds and subsequent quenching for 1.5 seconds using a water-emulsion medium. The average heat transfer coefficient utilized during the quenching phase was established based on observations of microstructures in trial samples, resulting in an optimized value of 35000 W/m^{2}K.

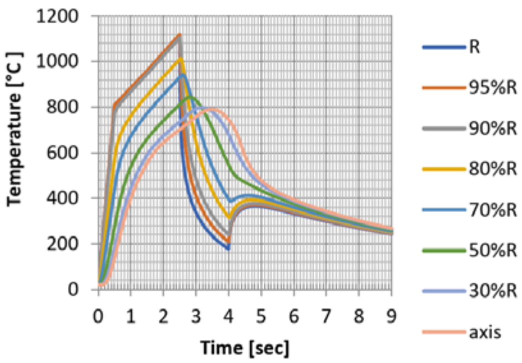

Fig.5 Calculated temperature field in planetary shaft during induction hardening process (htc = 35000 W/m^{2}K)

Fig. 6 exhibits photographs of the heat-treated planetary shaft, displaying the shaft itself in the upper image and its longitudinal cross-section in the lower image. The hardened case appears clearly delineated and exhibits an approximate thickness of 1.4 mm. The cutting was performed using a water jet cutting machine.

Fig.6 Heat treated shaft (above) and longitudinal cross-section of the planetary shaft (below)

The microstructures along the cross-sectional line at different depths beneath the surface (as shown in Fig. 7) are depicted in Fig. 8.

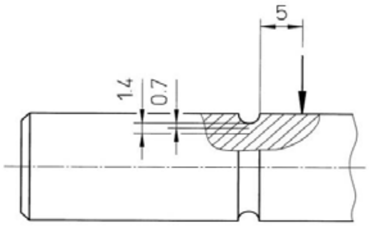

Fig.7 Cross-section line – microstructure analysis

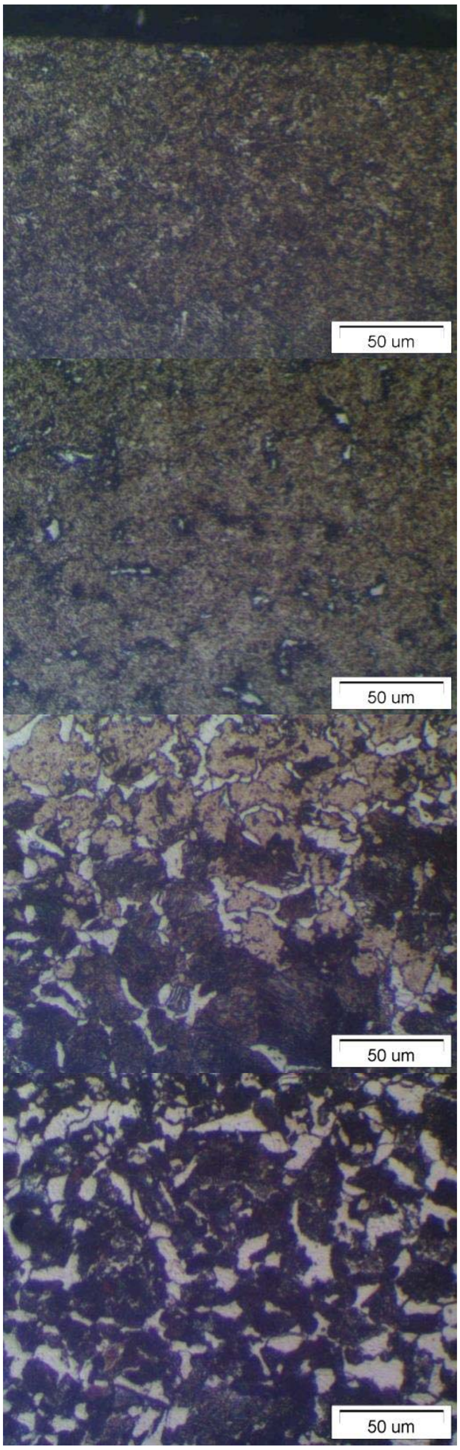

Fig.8 Steel microstructures at different depths under the surface: a) surface; b) 0.7 mm; c) 1.4 mm; d) 2.1 mm

At the surface of the shaft (a), the microstructure appears entirely martensitic. Moving to a depth of 0.7 mm beneath the surface (b), the microstructure comprises a mix of martensite and ferrite, indicating incomplete transformation into austenite during the induction heating period. The hardened case, approximately 1.4 mm in thickness (c), showcases constituents of martensite, pearlite, and ferrite within its microstructure. Below this depth (d), the microstructure consists primarily of pearlite and ferrite.

6 Conclusion

Our research focused on analyzing the induction spin hardening process applied to carbon steel planetary shafts used in diesel engine starters. To examine this, we conducted surface temperature measurements using a thermographic camera in the industrial environment of Slovenian company Iskra Avtoelektrika d.d.

These measurements involved monitoring the planetary shaft's temperature during the induction spin-heating phase. To ensure accuracy in temperature measurement using the thermographic camera, we conducted comparative temperature measurements. This involved heating the same planetary shaft in an electro-resistant furnace while simultaneously measuring its temperature with both a thermograph and the thermographic camera. The best-fit emissivity value utilized for the thermographic camera was determined as 0.7.

Utilizing a mathematical model, we developed a computer program specifically designed for calculating temperature distribution within the planetary shaft. The boundary condition (htc = 35000W/m2K) used for numerical calculations was derived from observations of the microstructure of test precursors.

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NOTE

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