Industrial Engineering Letters
ISSN 2224-6096 (Paper) ISSN 2225-0581 (online)
Vol.5, No.4, 2015 

# Surface Layer Modelling for Materials under Thermal Hardening Process

Salam J. Bash AlMaliky* Zainab Qahtan AlKhayat Jinan Abdulhassan Abdulnabi
AlMustansiriya University, Iraq
salambash2000@yahoo.com

**Abstract**
classification of the work tool's heat removal system was made via the analytical researches of the thermal physics of the thermal hardening processing of the machine parts' surfaces and on the basis of numerical and physical simulation of processes that take place in the contact area, with the aid of mathematical models for the effective relevant parameters. These parameters made it possible to implement the material nano-structuring of the surface coating. It was determined that the material nano-structuring of the parts of surface coating during that process using the criteria of plastic structure formation and processing rate is generally effective when the work tool with the in-line cooling heat removal system of the hollow indenter is used by the lubricating/cooling medium under pressure.
**Keywords:** heat removal, indenter, model, surface coating, thermal hardening.

## Introduction

Hard layer often appears at the exterior layer of low alloy steels of moderate carbon content and plain carbon as a result of thermal hardening through heating till it reaches the austenistising temperature (around 850$^{o}$C, depending upon carbon content) then suddenly quenching it to end with a martensitic structure, the rate of heating would control the depth of hardening (Senthilkumar and Ajiboye, 2012). The control of such processes would be significantly promoted via the formulation of numerical or mathematical models. The thermal analysis was found effective for the handling the nano-structuring temperature control problem as compared to other mathematical modelling methods (Thomas et al. 1987). Nevertheless, coating material surface`s negative stability shift and complex heat removal from the contact area of the instrument with the in-process part surface, are the main obstacles against the use of this method in analysis of part surface coating formation after thermal hardening processing (ANSYS Inc., 2009). The aim of this research is to determine a scheme for mathematical simulation model to solve describe and control the nanostructure exterior layers of coating materials as a consequent of thermal hardening process, that takes into consideration, the lowest temperature of critical phase of the negative stability of working steel.

## Analysis setup

Mathematical modeling of maximum temperature in the deformation base at different plans of heat removal from instrument indentation, used at thermal hardening processing of part surfaces, with equivalent thermal scheme is made based on matrix method using Kirchhoff's and Ohm's laws by constructing the equivalent circuit (Aldo et al., 2009). The equivalent circuit for such a generalized equivalent thermal scheme of thermal hardening process with the configuration options of the heat removing system is illustrated in Fig. 1.

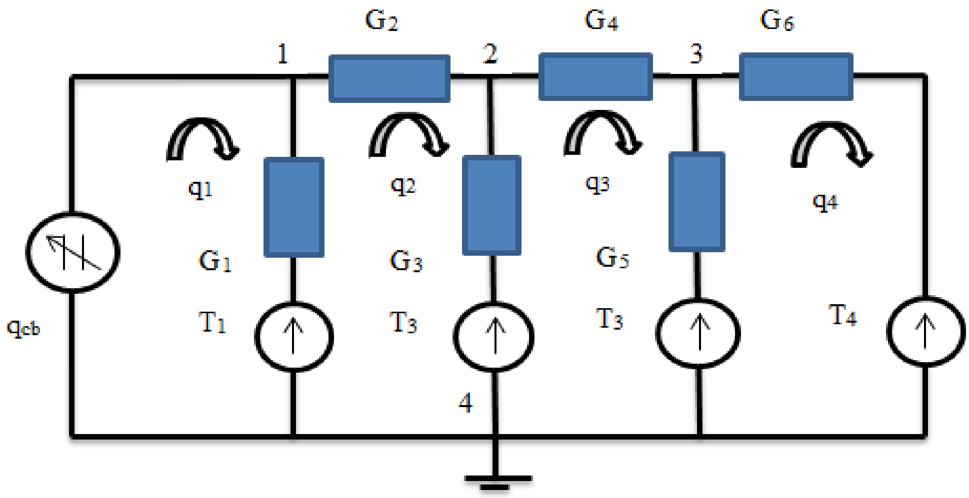


Fig. 1. Equivalent circuit of the generalized equivalent thermal scheme of nano-structuring thermal hardening process with heat removal through the instrument indenter

 

Thermal resistances were represented in the form of conductivity $G$ and determined correspondences of nodal conductions $G_{ij}$ and temperatures $T_i$. in order to determine the equivalent circuit`s nodal temperatures and the other goal of parametric analysis of heat removing system. Accordingly, the mathematical model of thermo-physics nano-structuring thermal hardening processing of part surfaces was represented by the following heat-balance equations for all possible configurations of the heat removing from the contact area of the instrument indenter with the working material:

$$\begin{aligned} G_{11}T_1 - G_{12}T_2 - G_{13}T_3 &= q_1 \\ - G_{21}T_1 - G_{22}T_2 - G_{23}T_3 &= q_2 \\ - G_{31}T1 - G_{32}T_2 - G_{33}T_3 &= q_3, \end{aligned} \tag{1}$$

where $G_{ij}$ – calculated nodal conductivity; $q_i$ – nodal heat flows; $T_i$ – nodal temperature.
In general, the mathematical model of the thermo-physics process for n-nodes equivalent circuit scheme of a generalized thermal equivalent scheme can be written in matrix form:

$$T^n G^n = q^n, \tag{2}$$

where $T$, $G$, $q$ – nodal temperature matrix, calculated nodal conductivity and nodal heat flows respectively.
Particular model to define highest item's material temperature in near-surface coating for adiabatic conditions of nano-structuring has the following form:

$$T_1 = q_{\mathrm{ncv}} \frac{1}{G_1} + T_{\mathrm{n}} \tag{3}$$

where $T_{\mathrm{n}}$ – initial temperature of the part surface coating material.
The use of the equivalent thermal scheme for the control of heat removal problem may be considered as a special case of the finite-difference method. Accordingly, the precision of nodes temperature determination of the equivalent scheme is primarily linked to the adequacy of mathematical formulation for thermal scheme resistances. As heat flow $q_z$ from high-speed transmitter of a capacity of $q_{\mathrm{ncv}}$ is perpendicularly spread to processing speed vector $v$, thermal bulk resistance of the heated bulk material $R_{\mathrm{mz}}$ is calculated as following:

$$R_{\mathrm{mz}} = \frac{4}{\pi} \frac{h_{\mathrm{n}}}{\lambda_{\mathrm{m}} l_{\mathrm{ck}}^2}, \tag{4}$$

where $h_{\mathrm{n}}$ – thickness of the surface coating part heated during thermal hardening processing; $\lambda_{\mathrm{m}}$ – thermal conductivity of the item's material; $l_{\mathrm{ck}}$ – length of the contact area.
High-speed heat generation from the part surface $q_{\mathrm{ncv}}$ heats surface coating material during the thermal hardening process, through the quasi-stationary seat of deformation $t_{\mathrm{n}}$ (Ludema, 1996), hence, the following relation would be used for the determination of the thickness of heated coating surface $h_{\mathrm{n}}$ can be defined as:

$$h_{\mathrm{n}} = \sqrt{3\lambda_{mz} t_{\mathrm{n}} / 2\mathrm{c}_{\mathrm{mz}} \rho_{mz}}. \tag{5}$$

And expression (4) may be rewritten as follows accordingly:

$$R_{\mathrm{mz}} = \frac{4\sqrt{3\lambda_{\mathrm{mz}} t_{\mathrm{n}} / 2c_{\mathrm{mz}} \rho_{\mathrm{mz}}}}{\pi \lambda_{\mathrm{mz}} l_{\mathrm{ck}}^2}. \tag{6}$$

Volume thermal resistance to the flow in material near-surface coating $R_{\mathrm{opc}}$ subjected to intensive plastic shift deformation under thermal hardening process is defined by its thickness that is equal to the depth of shift crest voltage and thermal conductivity $\lambda_{\mathrm{mz}}$, depending on structure plasticity at nano-structuring process and stored shift deformation degree:

$$R_{\mathrm{opc}} = \frac{4}{\pi} \frac{h_{\sigma xy}}{\lambda_{\mathrm{pc}} l_{\mathrm{pk}}^2}. \tag{7}$$

Contact thermal resistances to heat flow $q_{\mathrm{i}}$ occur in thin near-surface coating of deforming material $R_{\mathrm{kpz}}$ and on the instrument indenter surface in conditions of full crumpling initial micro shape of working part surface $R_{\mathrm{kpi}}$. The voltages subjected by the line contraction effect of heat flow $q_{\mathrm{i}}$ in the indenter contact area $l_{\mathrm{ca}}$ were found small as compared to the working surface geometric dimensions as illustrated by Fig. 2 (Lienhard IV and Lienhard V, 2011).

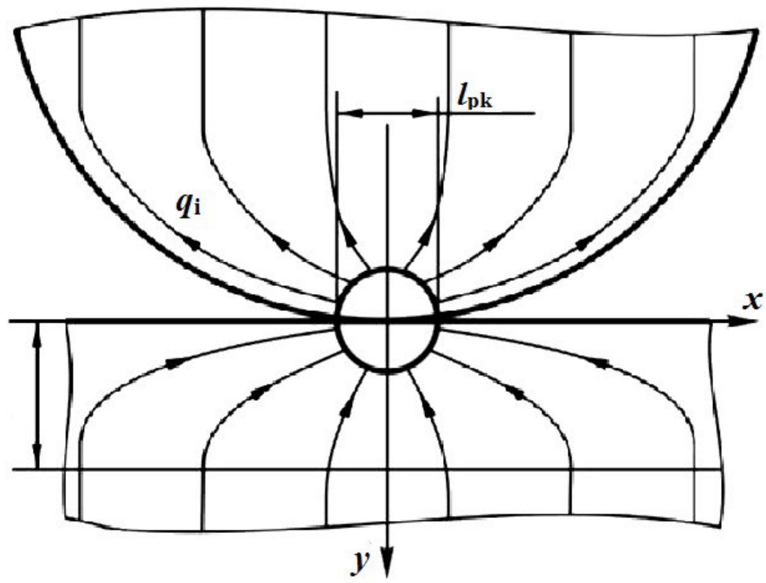


Fig. 2. The scheme of the indenter`s contact area

Rapid change of the material's temperature in the boundary layer of the work part and on the surface of the indenter takes place due to the supply of heat constriction $q_i$ through joint thermal resistances $R_{kpz}$, $R_{kpi}$ (Bahrami, 2002), these resistances may be determined as follows:

$$R_{kpz} = \frac{1}{\pi d_{pk} \lambda_{pc}}; \quad R_{kpi} = \frac{1}{\pi d_{pk} \lambda_{r}}, \tag{8}$$

where $\lambda_r$ is the indenter`s material heat conductivity.
The relevant heat sink areas of the $A_{tno}$, $A_{tvo}$ and heat-transfer coefficients $\alpha_{no}$, $\alpha_{vo}$, are of essential role for the calculation of the joint thermal resistances due to the convective heat transfer on the boundary with the cooling environment $R_{kno}$ and the indenter`s mandrel resistance for the internal cooling environment $R_{kvo}$ according to the following relations(Merrill and Garimellam 2011):

$$R_{kno} = \frac{1}{\alpha_{no} A_{tno}}; \quad R_{kvo} = \frac{1}{\alpha_{vo} A_{tvo}}. \tag{9}$$

Although the joint thermal resistance of the moving junction is greatly dependent on the roughness parameters and micro hardness of the contacting surfaces which control actual heat transfer area and determine the appearance of the additional resistance constriction $R_{kzk}$, the experimental researches showed that when in the work tool the dragging damper with a lapped face of the indenter carrier and the guide paths are used, the quantity of the joint resistance $R_{kzk}$ is negligible. there evidenced a volumetric thermal resistance of the split $R_{ozk}$ when the cylinder guide split $\Delta_z$ filled with the lubrication fluid with thermal conductivity $\lambda_{mz}$ , this can be demonstrated by the following relation:

$$R_{ozk} = \frac{\ln \frac{r_к}{r_i}}{2\pi \lambda_{mz} l_z}, \tag{10}$$

where $r_к$ and $r_i$ are the radiuses of the work tool's case and indenter, respectively; $l_z$ is the split surface length.

A generalized formula for calculation of thermal volumetric resistance $R_{om}$ of the work tool indenter's units (working part $R_{opz}$ and mandrel $R_{oop}$) was produced on the basis of equations 6 – 10 and experimental researches for calculation of the joint resistances $R_{mz}$, $R_{opc}$, $R_{kpz}$, $R_{kpi}$ $R_{kno}$, $R_{kvo}$, $R_{ozk}$. This in turn paves the way for the mathematical models of thermal resistances of equivalent heat scheme of the thermal hardening process of the machine parts' surfaces:

$$R_{om} = \frac{h_e}{\lambda_{et} A_{tn}}, \tag{11}$$

where $h_e$, $\lambda_{et}$ and $A_{tn}$ are the altitude, thermal conductivity and the heat transmission area of the work tool part, respectively.

The mathematical model analysis of the thermal process at the contact area during the thermal hardening process, has led to the conclusion that it is crucial to provide the proper fluid flow $Q$ in order to produce the most effective turbulent flow regime of the, in-line cooling system, lubricating/cooling medium, according to the relation:

$$Q > \frac{\mathrm{Re}_t \cdot v \cdot A}{d_n - d_t}, \tag{12}$$

where $\mathrm{Re}_t$ is the Reynolds number which corresponds the turbulent flow regime of the accepted lubricating-cooling technological environment; $v$ is the agent`s kinematic viscosity; $A$ is the cross-section area of the turbulence stimulator channel in the work tool configuration; $d_n$ is indenter's cage inside diameter; $d_t$ is the turbulence stimulating pipe`s outside diameter.

## Conclusion

Mathematical modelling of the process of thermal hardening that affects the in-process material`s exterior surfaces is demonstrated via the equivalent thermal scheme in which the material's thermal resistances of outside layer of the functioned part are embodied by the reciprocal value of junction conductivity with reference to the exterior layer material and the work tool's heat removal system units, taking into consideration that the number of segregating parts of the equivalent heat scheme (thermal resistances) depends on the kind of heat removal system in accordance with the technique of cooling setting work tool`s supply to the indenter. the maximum temperature in the contact area of deformation region and corresponding processing speed, was determined as a critical concern for the hardening work tool in order to decide the exterior layer material that develops into the critical state of shift instability.

## References


- Aldo Boglietti, Andrea Cavagnino, David Staton, Martin Shanel, Markus Mueller, and Carlos Mejuto, (2009). Evolution and Modern Approaches for Thermal Analysis of Electrical Machines. IEEE Transactions on industrial electronics, Vol. 56, No. 3, DOI: 10.1109/TIE.2008.2011622.
- ANSYS Inc., (2009). Thermal Analysis guide.
- Bahrami M. (2002). Modeling of Thermal Joint Resistance for Rough Sphere-Flat Contact in a Vacuum. Waterloo university, Ontario.
- Lienhard IV J. and Lienhard V J., (2011). A heat transfer text book. 4th. Edition. Phlogiston press, Cambridge, USA.
- Otilia Nedelcu and Corneliu Ioan Sălişteanu (2012). Calculation Methods for Heating and Ventilation System of Electrical Machines, Heat Transfer Phenomena and Applications, ISBN: 978-953-51-0815-3, InTech, DOI: 10.5772/51962.
- Piotr Nieslony, Wit Grzesik, Piotr Laskowski, Witold Habrat (2013). FEM-Based Modelling of the Influence of Thermophysical Properties of Work and Cutting Tool Materials on the Process Performance. Procedia CIRP, Volume 8, 2013, Pages 3–8.
- Ludema Kenneth C, (1996). Friction, Wear, Lubrication: A Textbook in Tribology. CRC Press.
- Merrill, C. and Garimella, S V., "Measurements and Prediction of Thermal Contact Resistance across Coated Joints" (2011). CTRC Research Publications. Paper 235. DOI:10.1080/08916152.2010.503311.
- Senthilkumar T., and Ajiboye T. K. (2012). Effect of Heat Treatment Processes on the Mechanical Properties of Medium Carbon Steel. Journal of Minerals & Materials Characterization & Engineering, Vol. 11, No.2 pp.143-152.