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Experimental and numerical studies of AISI1020 steel in grind-hardening

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A B S T R A C T

Currently, most of the researches studying grind-hardening have used Design of Experiments approach to obtain empirical correlations without any in-depth theoretical analyzes. In this paper, a comprehensive numerical model is developed to simulate the temporal and spatial temperature distributions of the workpiece under the dry grind-hardening condition using finite element method. The simulated hardness penetration depth is deduced from the local temperature distribution and time history of workpiece and its martensitic phase transformation conditions. The results from simulations are validated with experiments. The effect of two major grinding parameters, workpiece speed and depth of cut, on the hardness penetration depth are discussed.

1. Introduction

In any grinding processes, the heat generated in the grinding process causes the workpiece and wheel temperatures to rise. The high temperatures could cause various forms of thermal damages, such as workpiece burns. In the past, almost all of researchers tried to eliminate the grinding heat in grinding zone to avoid the grinding burns. In this paper, however, a new technology named grind-hardening is introduced. Due to the significant heat generated during the grinding process, the surface temperature of the workpiece, which rose by the grinding heat, is higher than the austenitizing temperature. This is then followed by rapid cooling to achieve the purpose of surface hardening. Simply speaking, this technology utilizes the dissipated heat in grinding zone to harden the surface layer of the workpiece. It is worth noting that this technology has the potential to fully integrate the surface hardening processes, such as flame hardening, laser hardening [1] and so on, into the production line, and thus reducing manufacturing processes and increasing productivity [2–5].

The grind-hardening technology has been widely studied by many researchers [2–4]. Most of the researches studying grind-hardening have used design of experiments approach [e.g., 2–4], by varying processes parameters with a great deal of experiments. However, due to the complexity of grinding processes [6,7], this approach often makes experimental studies with significant degree of uncertainty of the results. In the past, the thermal analysis of grinding process has been performed by using of finite element method in grind-hardening [8–14]. In this paper, temporal and spatial temperature distributions of the workpiece under grind-hardening condition are simulated based on finite element method. The simulated hardness penetration depth is deduced from the local temperature distribution and time history of workpiece and its martensitic phase transformation conditions. The actual experiment of grind-hardening on a steel workpiece, AISI1020, is carried out in grinding machine using surface grinder, M 7120 A. The metallurgical microstructure, depth and hardness of transect phase transformation layer are analyzed. The results from numerical simulations are validated with experimental data. Furthermore, the effect of two major grinding parameters, table speed and depth of cut, on the hardness penetration depth are presented and discussed in details.

2. Theoretical analysis

In any grinding processes, the grinding heat generated in the grinding zone is removed by the grinding wheel, workpiece, chips and the grinding fluid. Fig. 1 illustrates a typical horizontal grinding process. In this study, a dry grinding process is pursued since the main purpose is to use the grinding heat to harden the surface. The rate of heat transfer into the workpiece and its subsequent temperature distribution will be studied for the grind-hardening process.

2.1. The heat flux into the workpiece

When the grinding wheel cuts into the workpiece along the grinding zone, almost all of the mechanical energy converts into thermal energy [15]. The total grinding energy can be calculated as follows:

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Nomenclature

P_c	The grinding energy unit area, W/mm^2
F_t	The tangential force of grinding, N
V_s	The wheel speed, m/s
V_w	The table speed, m/s
b	The grinding width, mm
l	The geometrical contact length between the workpiece and the wheel, mm
a_p	Depth of cut, mm
d_s	The diameter of the grinding wheel, mm
Q_w	The heat flux into the workpiece, W/ mm^2
$(kpc)_w$	The workpiece thermal contact coefficient, w/m k
k_g	The grain thermal contact coefficient, w/m k
k_x,k_y,k_z	The thermal conductivity x, y and z direction w/m k
n_x,n_y,n_z	The normal direction cosine
t	The time, s
r_0	The wear flat radius
θ^e	The temperature matrix
e	The symbol of matrix
T	Transposes the mark
N	The interpolating function matrix
n^e	The number of the nods in each element
Γ_1,Γ_2,Γ_3	The boundary conditions
ATL	The austenitizing temperature line
$\theta_{wb,s}$	The workpiece surface temperature

Greek Symbols

α	The convective heat transfer coefficient
ρ	The material density, kg/m^3
c	The material specific heat, J/(kg k)
ε	The energy partition of the heat transfer into the workpiece,

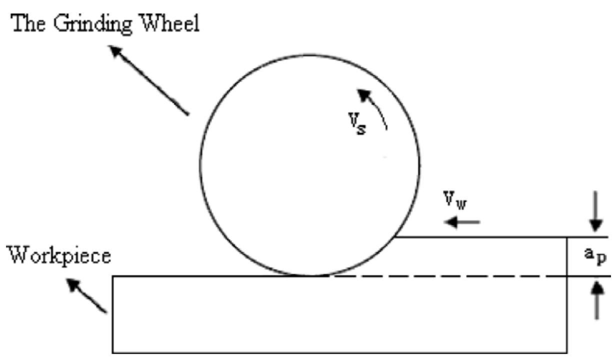

Fig. 1. The grinding geometry.

$$P_c = \frac{F_t V_s}{bl} \quad (1)$$

where P_c is the total grinding energy, F_t is the tangential force of grinding, V_s is the wheel speed, b is the grinding width and $l$is the geometrical contact length between the workpiece and the wheel (grinding zone length).

The value of l can be calculated as follow [16]:

$$l = \sqrt{a_p \cdot d_s} \quad (2)$$

where a_p is depth of cut, d_s is the diameter of the grinding wheel.

The heat flux into the workpiece can be described as follow:

$$Q_w = \varepsilon P_c = \varepsilon \frac{F_t V_s}{bl} \quad (3)$$

where Q_w is the heat flux into the workpiece, ε is the energy partition of the heat transfer into the workpiece. The value of ε [17] can be estimated as follow:

$$\varepsilon = \left(1 + \frac{k_g}{\sqrt{r_0 V_s}} \times \frac{1}{\sqrt{(kpc)_w}}\right)^{-1} \quad (4)$$

where $(kpc)_w$ is the workpiece thermal contact coefficient, r_0 is the wear flat radius;k_g is the grain thermal conductivity.

2.2. Mathematical model of the temperature field

Considering the complexity of this technical problem, many of the researchers seek numerical solution by using of the modern mathematics, mechanics theory and the computer. Since the grinding process is mostly in transient state, therefore, the finite element transient temperature field theory of the mathematical model is introduced as follows.

The temperature distribution in the grinding zone is due to the action of many individual grains producing heat at discrete points of the workpiece surface. A method [17,18] that has been widely used in the grinding heat transfer analysis is to consider the temperature distribution to be the superposition of a "background" temperature rise and the "peak" temperature rise which occur only under individual grains. It has been shown experimentally that from the point of view of predicting the metallurgical transformation to the workpiece, it is the workpiece "background" temperature that is of interest, not the peak temperature that occurs under a grain [18]. The reason for this is that the peak temperature occurs for a very short time, and austenitization requires time to occur. The workpiece "background" temperature rise is calculated using the heat entering the workpiece, and distributing in some fashion usually uniform, over the entire grinding zone. In this paper, the workpiece "background" temperature will be simply called workpiece temperature.

The grinding zone is assumed to be a plane heat source with triangular heat flux distribution in the grinding zone. The width of the plane heat source is equal to the width of the workpiece. According to the law of conservation of energy, the general three-dimensional transient heat conduction equation of the grinding temperature distribution in the workpiece can be expressed as,

$$\rho c \frac{\partial \theta}{\partial t} - \frac{\partial}{\partial x}\left(k_x \frac{\partial \theta}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial \theta}{\partial y}\right) - \frac{\partial}{\partial z}\left(k_z \frac{\partial \theta}{\partial z}\right) - \rho Q = 0 \quad (5)$$

In order to solve the equation, the following boundary conditions are specified in the computational domain. This computational domain is denoted as Ω. Here, the Ω region is composed by three kinds of boundary conditions (see Fig. 2 for details):

Γ_1 boundary condition

$$\theta = \bar{\theta} \quad (6)$$

Γ_2 boundary condition

$$k_x \frac{\partial \theta}{\partial x} n_x + k_y \frac{\partial \theta}{\partial y} n_y + k_z \frac{\partial \theta}{\partial z} n_z = q \quad (7)$$

Γ_3 boundary condition

$$k_x \frac{\partial \theta}{\partial x} n_x + k_y \frac{\partial \theta}{\partial y} n_y + k_z \frac{\partial \theta}{\partial z} n_z = \alpha(\theta_a - \theta) \quad (8)$$