



**A NUMERICAL INVESTIGATION INTO THE
MECHANISMS OF RESIDUAL STRESSES INDUCED
BY SURFACE GRINDING**

by

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Finally, I wish to dedicate this thesis to my wife for her continued encouragement, help and love.

Declaration

I declare that this thesis contains no material which has previously been presented for the award of any other degree or diploma in any university or institution, and to the best of my knowledge the material is original except where due reference is made in the text of the thesis.

Mofid Mahdi

Abstract

Grinding introduces unavoidable residual stresses of significant but unknown magnitudes. The effect of residual stresses in surface integrity is related to the nature of the residual stresses which relies purely on the process parameters and the workmaterial properties. It is a well-known fact that the fatigue strength of a ground component is increased by introducing compressive stresses. On the other hand, fatigue cracks may originate at regions of maximum tensile stress and usually at the surface of the material. Moreover, stress corrosion cracking is another consequence of critical surface tensile stress. Added to that, the residual stresses may result in dimension alteration and surface distortion, particularly for thin products such as plates.

The beneficial effects of compressive residual stresses have been widely recognized in industry. The wise application of such a principle would bring about improved economical use of parts subjected to fatigue loading and aggressive environmental conditions. Therefore a better understanding of residual stress mechanisms is necessary to increase the dimensional accuracy and improve the surface integrity of ground elements, particularly for parts with high precision and manufactured by automated production lines. Consequently, the development of reliable models for predicting residual stresses is of great value in reducing the amount of measurements and experimental tests of residual stresses. Unfortunately, little effort has been devoted so far to develop appropriate models to take into account grinding conditions, workmaterial properties and boundary conditions.

This thesis aims to investigate the residual stress mechanisms induced by grinding in terms of grinding parameters. In order to obtain a full understanding, both the roles of individual factors causing residual stresses (i.e. mechanical, thermal and phase transformation) and their couplings were carefully studied with the aid of the finite element method. The studies include:

- (1) residual stresses due to thermal grinding conditions,
- (2) residual stresses due to iso-thermal mechanical grinding conditions,
- (3) coupling of thermo-mechanical conditions,
- (4) coupling of thermo-phase transformation, and
- (5) the full coupling of all the factors.

It is found that under sole thermal grinding conditions, the heat flux associated with up-grinding may lead to a higher grinding temperature compared with that of down-grinding. A constant flux introduces the least temperature rise if the total grinding energy is the same. Higher convection heat transfer not only decreases the grinding temperature but also makes the temperature rise occur mainly within a thin surface layer. A similar effect can be achieved by applying higher table speeds.

When the grinding temperature is less than the austensing temperature, surface residual stresses are tensile. The heat generated within the grinding zone causes a very non-uniform temperature field in the workpiece. The part of the workmaterial subjected to a higher temperature rise expands more significantly and causes compressive stresses because of the restraint from its surrounding material that expands less. When the surface heat flux moves forward, the material outside the grinding zone contracts under cooling. Since the workmaterial has been plastically deformed during thermal loading, the contraction is restrained and thus a tensile stress field is generated locally.

If a workpiece material experiences a critical temperature variation in grinding, phase transformation takes place and a martensite layer appears in the immediate layer underneath the ground surface. It was found that the growth of martensite develops a hardened zone with a higher yield stress that expands with the movement of the heat flux. A tensile surface residual stress is then developed. When the volume growth of material takes place during phase change, compressive residual stresses may also be generated.

Under iso-thermal grinding conditions, it was found that plane stress is mainly compressive regardless of the distribution of surface traction and the direction of the tangential grinding force. With up-grinding, the residual stress in the grinding direction is always tensile. However, down-grinding may yield compressive surface residual stresses if the magnitude of the ratio of horizontal to vertical grinding forces is sufficiently large. Moreover, it is noted that discrete surface traction, which is more reasonable in terms of simulating the individual cutting of abrasive grits, would bring about more complex residual stress distribution that is very sensitive to the combined effect of individual cutting grits.

If thermal and mechanical grinding conditions are coupled, a state free from residual stresses may be achieved if grinding heat is low and either the convection heat transfer or the table speed is high. However, it is found that the full coupling of the mechanical deformation, the thermal deformation and deformation by phase change results in tensile residual stresses. The effects of cooling and mechanical traction in this case however are minor.

In summary, the research of this thesis explored the following: **(a)** grinding temperature development in terms of a wide range of grinding parameters together with the effect of temperature-dependent material properties, **(b)** the origin and onset of irreversible deformation due to mechanical loading, thermal loading and phase change under critical grinding conditions, **(c)** the effects of individual residual stress mechanisms and their partial and full couplings, and **(d)** the selection of grinding conditions to achieve beneficial residual stresses.

Finally, based on the new findings in this research, a more comprehensive methodology is suggested for further study.

List of Symbols and Abbreviations

a	thermal coefficient of expansion of workmaterial
B_c	dimensionless coefficient of specific heat, $b_c q L_c / 2 k_\infty$
B_k	dimensionless coefficient of thermal conductivity, $b_k q L_c / 2 k_\infty$
b_c	coefficient of specific heat, $(1 - k/k_Y)/T$
b_k	coefficient of thermal conductivity, $(1 + c/c_Y)/T$
Cr_{700}	cooling rate at 700 °C
c	specific heat capacity per unit volume of workmaterial
d	martensite depth
D	dimensionless martensite depth ($2d/L_c$)
\mathbf{D}	elastic-plastic constitutive matrix
E	modules of elasticity
e	error
F	force
H	non-dimensional heat transfer coefficient ($2ah/kv$)
Hv	Vickers hardness
h	heat transfer coefficient of coolant
L_c	length of grinding zone, see Fig 1
l_a	relative peak location of a heat flux ($2z_a/L_c$), see Fig 2.2b
M	martensite
Pe	Peclet number ($vL_c/4a$)
p	traction intensity
p_a	peak value of traction intensity
q	heat flux per unit grinding width
q_a	peak value of the heat flux
q_c	heat transferred by convection (hT), see Fig 2.2b
T	temperature rise with respect to ambient temperature T_∞
t	time
t_c	critical time required to force martensite transformation
\bar{t}	dimensionless time ($v^2 t / 2a$)
v	moving speed of the heat source, see Fig 2.2b

- Y yield stress of the workmaterial
 a thermal diffusivity
 ϵ strain tensor
 \mathbf{z}, \mathbf{c} coordinates, fixed to the moving heat source, see Fig 2.2b
 m ratio of horizontal to vertical grinding force
 k thermal conductivity of workmaterial
 u Poisson's ratio
 \mathbf{s} stress tensor
 w effective cooling factor within the grinding zone
 q dimensionless temperature, $T/(qL_c/2k_y)$

Subscripts

- c cut, grinding zone
 e elastic
 f finish
 m mechanical
 n normal, vertical
 s starts
 T thermal
 t horizontal
 wh wheel
 x,y,z x-, y- and z-directions, see Fig. 2.2b
 y yield
 \mathbb{Y} room temperature
 $1,2,3$ maximum, intermediate and minimum principal directions

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