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Temperature Effects on Grinding Residual Stress

Omar Fergani^a, Yamin Shao^a, Ismail Lazoglu^b, Steven Y Liang^{a*}^aGeorges W Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA^bDepartment of Mechanical Engineering, Koc University, Istanbul, Turkey* Corresponding author. Tel.: +404.894.8164; fax: +404.894.9342. E-mail address: steven.liang@me.gatech.edu

Abstract

Residual stress is a key factor that influences the reliability, precision, and life of final products. Earlier studies have alluded to the fact that the grinding process is usually the source of a tensile residual stress on the part surface, while there exists a temperature level commonly referred to as the onset tensile temperature beyond which the tensile profile of residual stresses starts to be generated. In this paper, a physics-based model is proposed to predict the onset temperature as a function of residual stress on an analytical and quantitative basis. The predictive model is based on the temperature distribution function using a moving heat source approach. Then, the thermal stresses are calculated analytically using Timoshenko thermal stress theory [1] followed by an elastic-plastic relaxation condition imposed on these stresses, thus leading to the resulting residual stresses. The model-predicted results have been experimentally validated using data of the grinding of AISI52100 hardened steel with subsequent X-ray and Neutron diffraction measurements. The model was shown to predict the residual stress profile under given process conditions and material properties, therefore providing an analytical tool for grinding process planning and optimization based on the understanding of onset tensile temperature for control of tensile residual stresses.

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1. Introduction

Grinding is a common finishing operation in the manufacturing industry and can be simplified as depicted in Figure.1. The properties of surface layer created in the grinding process will influence the functionality and reliability of the product such as fatigue strength and corrosion resistance. However, there are often-encounter contradiction issues between the productivity and the surface integrity. Higher material removal rate is always favorable in view of productivity, however, that could lead to the increase of grinding power and result in temperature rise in the contact zone. High temperature is likely to create high tensile residual stress on the workpiece surface which is detrimental to the product.

According to [2], there are three major causes for residual stress on the ground surface: thermal expansion and contraction, phase transformations, and plastic deformation. It

is found that thermal expansion and contraction can be the most important factor in the generation of tensile stresses [3]. Based on this fact, many researchers have studied the influence of grinding temperature on residual stress. [3, 4, 5, 6] However, an analytical solution to this problem has not been documented as of yet. Most of the results are experimentally based or FEA-based which can be time-consuming for process planning purposes. This paper presents the analytical investigations flanked on grinding mechanics to focus on the effects of thermal loading and temperature distribution on the generation of residual stress in ground parts. This is important for the fundamental understanding of the physics of the process and also for the control of residual stress. From previous research it is known that lower temperature will lead to reduced or elimination of tensile residual stresses [3], suggesting that there is a critical temperature for the onset of tensile residual stress [3, 4]. The critical temperature – onset tensile temperature – is greatly influenced by the flow stress of a specific material as proven

by several experimental studies. [3, 4]. In this work, a comprehensive model based on the analysis of thermal energy generation and temperature distribution is proposed assuming that the effect of mechanical stress is very small per previous experimental investigations [3, 4]. The model will be able to predict the onset temperature from which tensile residual stresses will be generated on the surface. The model was simulated for grinding of AISI 52100 and subsequently validated experimentally using data collected from x-ray and neutron diffraction from [4].

2. Physics-based modeling approach

2.1. Grinding temperature prediction

The thermal effects due to the grinding process have a significant effect on the produced residual stress. Previous work by [3, 4] have shown that elevated temperature result in tensile stress on the workpiece surface. Jaeger [7] proposed a method of determining the temperature rise based on moving heat source. Extension of his method has been often used in the literature. Among them, a triangular heat flux approximation is validated to be accurate for grinding. [8].

The heat flux in the contact zone is expressed as:

$$q = q_0 \left(1 + \frac{2x'}{l_c} \right) \quad (1)$$

where

$$q_0 = \frac{P}{l_c b} \quad (2)$$

The solution for the moving band heat source can be represented by Bessel functions and obtained by summing over the length of the contact zone. Based on the triangular moving band heat source model [8], the temperature at any point (x, z) in the workpiece is given as:

$$T_{(x,z)} = \int_{-\frac{l_c}{2}}^{\frac{l_c}{2}} \frac{q R_w}{\pi k} e^{-\frac{v_w(x-x')}{2\alpha}} K_0 \left\{ \frac{v_w \left[(x-x')^2 + z^2 \right]^{1/2}}{2\alpha} \right\} dx' \quad (3)$$

where (x, z) is the coordinate of a workpiece point. Figure.2 shows the obtained simulation results.

Nomenclature

q_0	average heat flux
P	grinding power
b	grinding width
l_c	contact length
$K_0(u)$	modified Bessel function
R_w	heat partition ratio to the workpiece
q	heat flux
v_w	workpiece speed
α	thermal diffusivity of the workpiece
k	thermal conductivity of the workpiece
G	elastic shear modulus
h	modulus function
κ	algorithm constant
M	number of increments taken in the relaxation process
G_{xh}	plain strain Green's functions
G_{xv}	
G_{zh}	
G_{xzh}	
G_{xzv}	
Ψ	
h/G	blending function
σ_{xx}, σ_{yy}	modulus ratio stresses

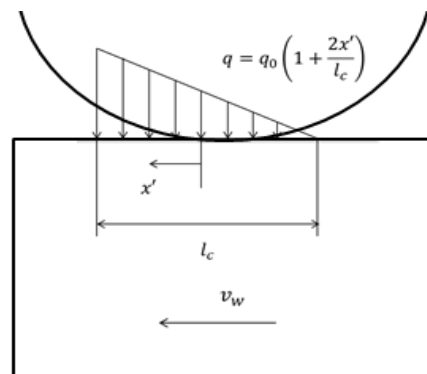


Fig.1. Grinding process and the heat source

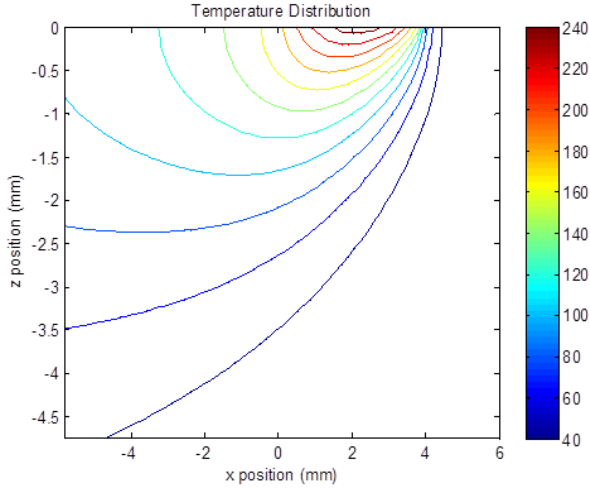


Fig.2. Simulated temperature for the grinding process

2.2. Residual stress model

Many previous works in the machining modeling tried to predict residual stress based on approaches associating both mechanical and thermal loadings. During the grinding process, the residual stresses generation process is slightly different from other manufacturing process such as machining. The large amount of heat generated is playing a key role in the definition of the type of residual stresses. As presented in the previous section, many experimental investigations have shown that the residual stress profile is expected to be tensile when the temperature reaches a threshold value called tensile onset temperature [3], while the effects of mechanical loading are less significant. The tensile onset temperature is the temperature beyond which the residual stress generated in grinding is tensile. Therefore, understanding the physical origin of this temperature is of the essence.

This work aims to identify analytically the onset temperature induced mainly as suggested in previous research [3] by the non-uniform heating effects. For this, the mechanical residual stresses are going to be neglected in this study. It is believed that the onset temperature position will vary slightly when the mechanical aspect is considered. Therefore the mechanical effect will be considered in a further study.

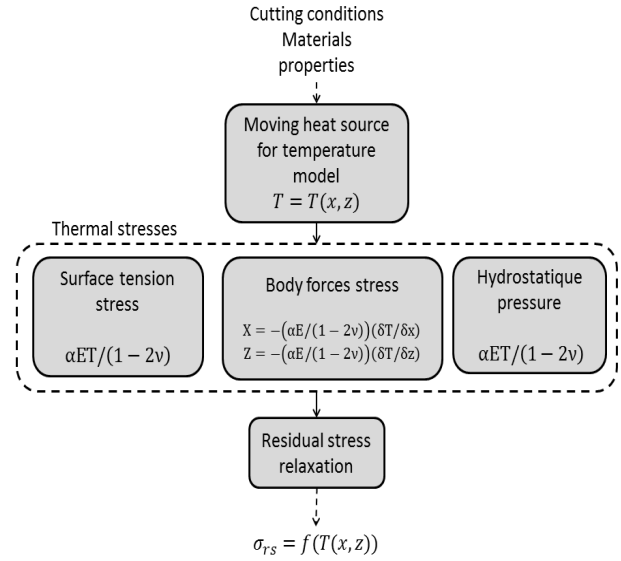


Fig.3. Flowchart of the procedure

The stress induced by the thermal loading and the temperature gradient generated by the grinding wheel are captured using [1]. This model has been used by [9] in the prediction of residual stresses in the orthogonal cutting case. Thermally generated stresses were first investigated by Timoshenko [1]. He proposed a three steps approach (Figure.3) to calculate the total thermal stresses and this by superposing the following component:

- Stresses due to body force $X = -(\alpha E/(1-2\nu))(\delta T/\delta x)$ and $Z = -(\alpha E/(1-2\nu))(\delta T/\delta z)$,
- Stresses due to a tensile surface traction of $\alpha ET/(1-2\nu)$,
- A hydrostatic pressure of $\alpha ET/(1-2\nu)$,

The resulting thermal stress components are given as

$$\sigma_{xx}^{therm} = -\frac{\alpha E}{1-2\nu} \int_0^{\infty} \int_{-\infty}^{\infty} \left(G_{xh} \frac{\partial T}{\partial x}(x', z') + G_{xv} \frac{\partial T}{\partial z}(x', z') \right) dx' dz' + \frac{2z}{\pi} \int_{-\infty}^{\infty} \frac{p(t)(t-x)^2}{((t-x)^2 + z^2)} dt - \frac{\alpha ET(x, z)}{1-2\nu} \quad (4)$$

$$\sigma_{zz}^{therm} = -\frac{\alpha E}{1-2\nu} \int_0^{\infty} \int_{-\infty}^{\infty} \left(G_{zh} \frac{\partial T}{\partial x}(x', z') + G_{zv} \frac{\partial T}{\partial z}(x', z') \right) dx' dz' + \frac{2z^3}{\pi} \int_{-\infty}^{\infty} \frac{p(t)}{((t-x)^2 + z^2)} dt - \frac{\alpha ET(x, z)}{1-2\nu} \quad (5)$$

$$\sigma_{xz}^{therm} = -\frac{\alpha E}{1-2\nu} \int_0^{\infty} \int_{-\infty}^{\infty} \left(G_{xzh} \frac{\partial T}{\partial x}(x', z') + G_{xzv} \frac{\partial T}{\partial z}(x', z') \right) dx' dz' + \frac{2z^2}{\pi} \int_{-\infty}^{\infty} \frac{p(t)(t-x)}{((t-x)^2 + z^2)} dt \quad (6)$$

where

$$p(t) = \frac{\alpha ET(x, z = 0)}{1 - 2\nu} \quad (7)$$

and ($G_{xh}, G_{xy}, G_{xh}, G_{zh}, G_{xzh}, G_{xzv}$) are the plain strain Green's functions as can be found in the literature [10].

$$\sigma_{yy}^{therm} = \nu(\sigma_{xx}^{therm} + \sigma_{zz}^{therm}) \quad (8)$$

Using the stress field calculated above, the residual stresses are computed from assuming a rolling/sliding contact case, as proposed by McDowell [11].

The hybrid model uses a blending function Ψ which is dependent on the instantaneous value of the modulus ratio h/G . Herein G is the elastic shear modulus, h the modulus function and κ an algorithm constant. The blending function is given as:

$$\Psi = 1 - \exp\left(-\kappa \frac{3h}{2G}\right) \quad (9)$$

Therefore the residual strain in both direction under the plane strain conditions can be calculated as:

$$\begin{aligned} \dot{\epsilon}_{xx} &= \frac{1}{E} [\dot{\sigma}_{xx} - \nu(\dot{\sigma}_{yy} + \dot{\sigma}_{zz})] + \alpha \Delta T + \\ &\frac{1}{h} (\dot{\sigma}_{xx} n_{xx} + \dot{\sigma}_{yy} n_{yy} + \dot{\sigma}_{zz} n_{zz} + 2\dot{\tau}_{xz}^* n_{xz}) n_{xx} \\ &= \Psi \left(\frac{1}{E} [\dot{\sigma}_{xx} - \nu(\dot{\sigma}_{yy} + \dot{\sigma}_{zz})] + \alpha \Delta T + \right. \\ &\left. \frac{1}{h} (\dot{\sigma}_{xx} n_{xx} + \dot{\sigma}_{yy} n_{yy} + \dot{\sigma}_{zz} n_{zz} + 2\dot{\tau}_{xz}^* n_{xz}) n_{xx} \right) \\ \dot{\epsilon}_{yy} &= \frac{1}{E} [\dot{\sigma}_{yy} - \nu(\dot{\sigma}_{xx} + \dot{\sigma}_{zz})] + \alpha \Delta T + \\ &\frac{1}{h} (\dot{\sigma}_{xx} n_{xx} + \dot{\sigma}_{yy} n_{yy} + \dot{\sigma}_{zz} n_{zz} + 2\dot{\tau}_{xz}^* n_{xz}) n_{yy} = 0 \end{aligned} \quad (10)$$

Solving these two equations simultaneously gives the increments in stresses $\dot{\sigma}_{xx}$ and $\dot{\sigma}_{yy}$. Then by integration over the loading passage the residual stresses can be determined.

Besides, the following boundary conditions are given by Merwin and Johnson:

$$\begin{aligned} (\epsilon_{xx})_r &= (\epsilon_{yy})_r = (\gamma_{xy})_r = (\gamma_{yz})_r = 0 \\ (\sigma_{xx})_r &= f_1(z) \quad (\sigma_{yy})_r = f_2(z) \end{aligned} \quad (12)$$

$$\begin{aligned} (\sigma_{zz})_r &= (\tau_{xz})_r = (\tau_{xy})_r = (\tau_{yz})_r = 0 \\ (\epsilon_{zz})_r &= f_3(z) \quad (\gamma_{xz})_r = f_4(z) \end{aligned} \quad (13)$$

In order to retain equilibrium, any non-zero components $(\sigma_{zz})_r, (\tau_{xz})_r, (\epsilon_{xx})_r$ are incrementally relaxed until the boundary conditions are met.

$$\Delta \sigma_{zz} = -\frac{(\sigma_{zz})_r}{M} \quad \Delta \tau_{xz} = -\frac{(\tau_{xz})_r}{M} \quad \Delta \epsilon_{xx} = -\frac{(\epsilon_{xx})_r}{M} \quad (14)$$

where M is the number of increments taken in the relaxation process. During relaxation, there are two kinds of material behavior: purely elastic relaxation and elastic-plastic relaxation

3. Results and validation

The proposed model was validated by the experimental results obtained by [4]. The same cutting conditions and materials systems were implemented in both model-prediction and experimentation. Grinding was carried out on one side of each sample on an Abwood HS5025CP grinding machine. An aluminum oxide wheel was used. Three wheel speeds ($v_s = 20, 30$ and 40ms^{-1}) and three workpiece speed ($v_w = 0.1, 0.2$ and 0.3ms^{-1}) were used. Depths of cut were in the range $0.53\text{--}10.63 \mu\text{m}$. Tables 1 and 2 present the material physical properties and Johnson-Cook flow stress model coefficients that were used in the computational implementation from [12].

Table.1 Material Properties for AISI 52100

E (GPa)	ν	Cp_0 (J/kg - C)	Kt_0 W/m ² C	ρ (kg/m ³)	α (um/m-C)	T_m (C)
200	0.28	475	46.6	7833	11×10^{-6}	1480

Table.2 Johnson-Cook coefficients for AISI 52100

A	B	C	m	n	D	E
1712	408	0.0211	1.21	0.391	1	1

The grinding force and power were calculated based on the grinding parameters and the heat partition into the workpiece was calibrated using the maximum grinding zone temperature. Figure 4 and 5 shows the obtained results. The curves are plotted for the surface of the workpiece.

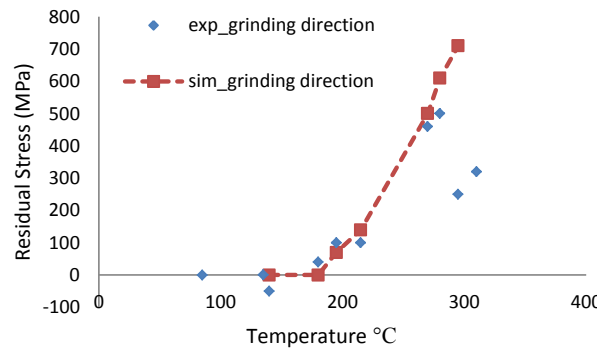


Fig.4 Residual stress vs. temperature in grinding direction on the surface

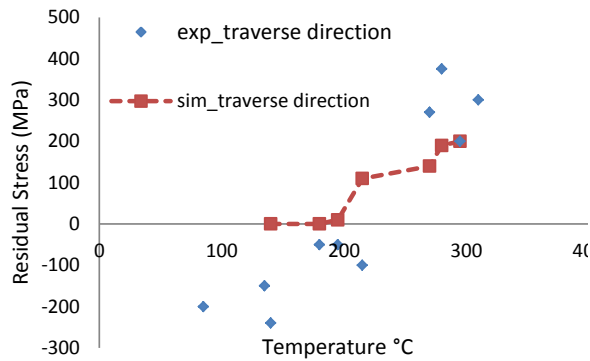


Fig..5 Residual stress vs. temperature in transverse direction on the surface

As shown in Figures 4 and 5, it can be observed that the onset temperature for the hardened steel AISI 52100 was around $T_{\text{onset}} = 190^{\circ}$ for both traverse and cutting directions. Above this grinding temperature, the residual stresses predicted and measure on the workpiece surface are tensile. The proposed model in this paper uses a new physics-based approach to predict residual stress generation as a function of grinding temperature with accuracy especially for the case of the grinding velocity direction. As stated in the introduction, the main objective of this work was to propose a mathematical model able to predict the tensile onset temperature from which the grinding process will likely lead to tensile residual stresses. The mechanical stress was neglected in this analysis as its effect is expected to be limited in the surface finishing processes, and this stipulation has been validated by the experimental data.

Conclusion

This paper presented the new development of a prediction model of the onset temperature responsible for the activation of the tensile residual stress on a grinded part surface. This model is based on a physics-based understanding of the elastic-plastic stresses and strains generated by a non-uniform heating operation in grinding. An approach based on three steps was pursued: The temperature generated by the grinding process was first predicted; then the thermal stresses composed of the body forces, surface traction and hydrostatic pressure were calculated analytically; then an elastic plastic relaxation procedure was applied to meet the stain compatibilities. The residual stress profile was expressed as a function of temperature, thus related to process parameters and material properties. The model-based simulations were experimentally validated in the case of AISI 52100 grinding for which the onset temperature was found to be around 190° for both cutting and transverse directions. The model-experimental comparison further justifies the assumption that mechanical stress has a limited effect on tensile residual stress generation. The results of this new study could provide a scientific basis for planning of grinding configuration and parameters in the interest of residual stress control.

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