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On The Temperature and Residual Stress Field During Grinding

S. M. H-Gangaraj, G. H. Farrahi and H. Ghadbeigi

***Abstract*—Grinding is widely used for manufacturing of components that require fine surface finish and good dimensional accuracy. In this study a thermo-mechanical finite element analysis is conducted to find out how grinding parameters can affect temperature and residual stress distribution in the workpiece. Results of parametric study presented in this work indicate, by carefully selecting the grinding parameters, minimum thermal and mechanical damage can be achieved. Higher workpiece velocities produce higher surface residual stress. By increasing depths of cut, depth of tensile residual stresses increases. Convection heat coefficient does not have any considerable effect on surface residual stress.**

***Index Terms*—Finite Element, Grinding, Residual Stress, Temperature Field.**

I. Introduction

Grinding is widely used amongst the most common machining process, especially, for manufacturing of components that require fine surface finish and good dimensional accuracy. Generally, grinding is used as a final machining process and therefore having a deep quantitative knowledge of effects induced by this process plays an important role in performing subsequent design calculations and service life estimation with a reasonable accuracy. Comparing with other machining process, grinding requires more energy per unit volume of material removal. Grinding is characterized by high temperatures and high friction, and most of the energy remains in the ground surface, resulting in high work surface temperatures which in turn can cause thermal damage and unfavorable residual stresses. These undesirable effects can adversely affect on strength, fatigue life and wear resistance of workpiece.

There are some efforts in the literature to measure or predict thermal and mechanical state of workpiece after grinding. Mahdi and Zhang [1], [2] developed a finite element model in which a moving heat source and pressure travels along a ground surface. They found that the model had good agreement with the existing analytical models. Mamalis et al. [3] used a similar thermal model to describe temperature field developed during grinding. Moulik et al. [4] extended their thermal study to obtain thermal induced residual stress. Their results showed for an elastic-plastic workpiece material, the near surface residual stress is predominately tensile and that the magnitude of this stress increases with increasing heat flux values. Experimental study carried out by Yu et al. [5] showed that stretch grinding can, under certain conditions, very effectively reduce the residual tensile stress in the surface layer of the workpiece or even convert the residual tensile stress into residual compressive stress. Anderson [6] offers two different thermal models, experimentally validated for shallow and deep grinding . However, a large number of these researches have been devoted to the thermal aspect of grinding and a clear relationship between grinding parameters and residual stress induced in ground component has not been presented so far. For this reason a finite element model of grinding is presented in the present work. For verification, the grinding parameters whose results had been reported in the literature were applied into the model. There has seen a good agreement between the two sets of results, providing some validation for the accuracy of the present analysis. By altering the grinding parameters such as depth of cut, coolant parameter and workpiece velocity, different grinding conditions were simulated.

II. Grinding Kinematics

Fig. 1 shows a schematic representative of a grinding process. Here a wheel rotating with a surface velocity of V_s traversed against the surface of workpiece with relative velocity of V_{wp}. During the process an amount of a i.e. “depth of cut” is removed from the surface. The contact length between wheel and workpiece is calculated from equation (1) in which l_c is contact length, d_s is diameter of wheel and a, as mentioned before is depth of cut that is removed in one pass. The heat flux that exerts to the workpiece during grinding can be calculated from equation (2) where q is heat flux into the workpiece, ε is percentage of heat flux entering into the workpiece, F_t is tangential force that produced during engagement of wheel and workpiece and b is the grinding width. The proportion of heat flux entering the workpiece can be calculated [3] by equation (3) where u_{ch} is the energy required for chip formation having a constant value of $13.8\ J/mm^3$ for grinding all ferrous materials [3], and u is the total specific energy required for grinding,

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calculated by equation (4) which according to [4] has a typical value of *55 J/mm*^{3} for steel.

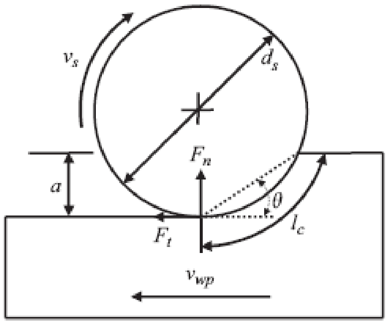

Fig. 1. Schematics of grinding [7].

$$lc = \sqrt{ad_s} \quad (1)$$

$$q = e\frac{F_t V_s}{bl_c} \quad (2)$$

$$e = 1 - \frac{u_{ch}}{u} \quad (3)$$

$$u = \frac{F_t V_s}{abV_{wp}} \quad (4)$$

III. FINITE ELEMENT MODEL

The process of grinding is carried out by movement of a workpiece under a rotating grinding wheel. During this process, surface of workpiece comes into contact with abrasive grains of grinding wheel and a certain amount of material is removed from it. At any defining moment contact occurs in a specific length of workpiece called contact length in which thermal exchange and mechanical forces are introduced into the workpiece. Consequently, problem of grinding, with all its complexities, can be described by moving an appropriate heat flux and mechanical forces on the top surface of workpiece, mathematically.

A two dimensional model was used to simulate movement of heat flux on the surface of workpiece using the ANSYS finite element analysis package. Since loading and geometry remains unchanged in the third direction, a two dimensional plane strain model would be appropriate for obtaining temperature and stress field. The finite element mesh is shown in Fig. 2. A finer mesh was used for subsurface layers of the work material in where steeper gradient of temperature and stress may occur. After running several models with different dimensions a control volume of the dimension of $8l_c \times 8l_c$ was selected based on the criterion that boundaries does not affect the distribution of temperature and residual stress field.

AISI 52100 bearing steel which is widely used for grinding [3], [4], [8] was considered for workpiece material. The thermal and mechanical properties of workpiece material are given in table I. Thermal analysis was carried out, step by step, by exerting calculated heat flux into the contact length. It is to mention that heat flux and the contact length are both functions of grinding parameters. Initial temperature of *20°C* was chosen for the workpiece and surrounding environment. For taking care the effect of coolant in grinding process, all over top surface except contact length, was exposed to convection heat transfer by introducing a heat convection coefficient into the model. Then, heat flux, as representative of grinding wheel, travelled all over the top surface. The necessary time was given until the workpiece cools down and reaches its initial temperature by exchanging heat with surrounding.

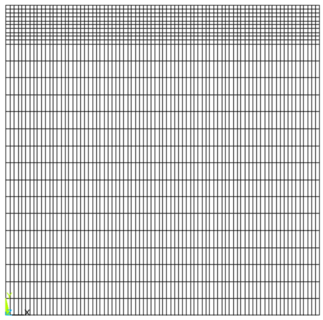

Fig. 2. Finite element mesh.

Table I. Thermal and mechanical properties of *AISI 52100* steel

Density, ρ	7800 kg/m^3
Conductivity, k	65 W/m °C
Specific Heat, C_p	500 J/kg °C
Thermal Expansion coefficient, α	1.5×10^{-5} m/m °C
Young’s Modulus, E	210 GPa
Poisson’s Ratio, ν	0.3
Yield Stress, σ_y	300 MPa
Plastic Modulus, H	10000 MPa

If the coupling of temperature and stress field is disregarded, which is the case of the present work, a sequential thermal mechanical analysis can be applied to determine thermal induced residual stresses. For this purpose, temperature history of the workpiece material was recalled into mechanical analysis and equilibrium equations were solved in each time step. Due to their very low magnitudes [3], [8], mechanical forces have a little effect in development of residual stress [2], [9] and therefore were neglected in this work.

IV. VERIFICATION

For verification of presented model, a numerical modelling based on experimental measurement of power consumed during grinding [3] was selected. Grinding parameters are listed in table II.

In depth temperature obtained by Mamalis et al. [3] and those obtained in present work are shown in Fig. 3. There is a good agreement between the two sets of results, providing some validation for the accuracy of the present analysis.

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Table II. Grinding parameters used for verification

Depth of Cut	0.02 mm
Workpiece Velocity	0.133 m/s
Wheel Velocity	28 m/s
Width	20 mm
Convection Coefficient	20000 W/m^2 ^{o}C
Initial Temperature	20 ^{o}C
Material	AISI 52100

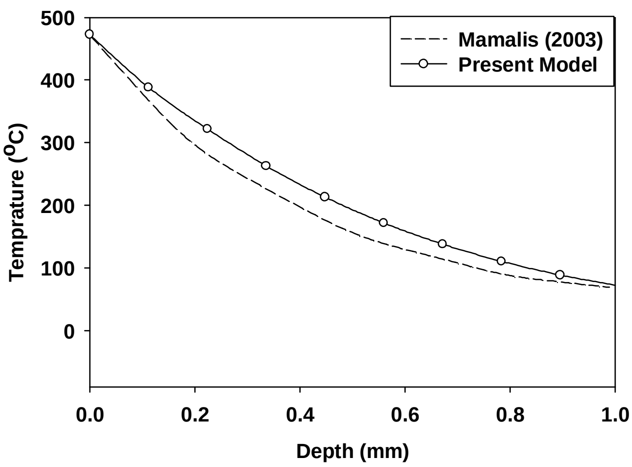

Fig. 3. Verification of presented model.

V. RESULT AND DISCUSSION

A. Effect of Workpiece Velocity

5 workpiece velocities, which are common in performing a grinding process [3], [10], were used: *0.02, 0.05, 0.13, 0.26, 0.4 m/s.* It was assumed that the depth of cut and grinding environment are the same for these different workpiece velocities. Therefore, depth of cut equal to *0.02 mm* and convection heat coefficient of *20000 W/m^2 ^{o}C* were applied in all models of this part. Width of *20 mm*, wheel velocity of *28 m/s* and wheel diameter of *250 mm* were kept constant for all models.

Variations of temperature by depth in the middle of workpiece are shown in Fig. 4. These data were obtained when heat flux reaches to the middle of the workpiece. So that it can be assumed that, these temperatures are the highest values of temperature which surface and subsurface layers in the middle of the workpiece experience during grinding. Calculations show that the peak temperature which takes place on the surface increases with increasing workpiece velocity. This is because a higher value of heat flux, generated at the contact, moves faster.

Effect of workpiece velocity on development of residual stress in a ground component is shown in Fig. 5. It can be seen from the results that grinding with higher workpiece velocities tends to higher surface residual stress. Calculations show that dependency of surface residual stress on workpiece velocity is more pronounce in lower amounts of velocity and there is a specific velocity after that surface residual stress does not encounter with tangible change. An interesting point to be considered is also, depth of tensile residual stress is the same for different workpiece velocities.

B. Effect of Depth of Cut

Here the influence of depth of cut on temperature and residual stress of ground components was investigated. This was done by fixing workpiece velocity at *0.13 m/s* and considering *20000 W/m^2 ^{o}C* as convection heat coefficient for three depths of cuts of *0.02, 0.05* and *0.1 mm*. The variation of temperature in depth as a function of depth of cut is shown in Fig. 6. This indicates as expected, removing a thicker layer of material in grinding process results in higher surface and subsurface temperature of work material. Depth of cut of *0.1 mm* in this study tend to near melting temperature in a ground surface which in turn increase the probability of thermal damage such as burning and phase transformation during subsequent cooling.

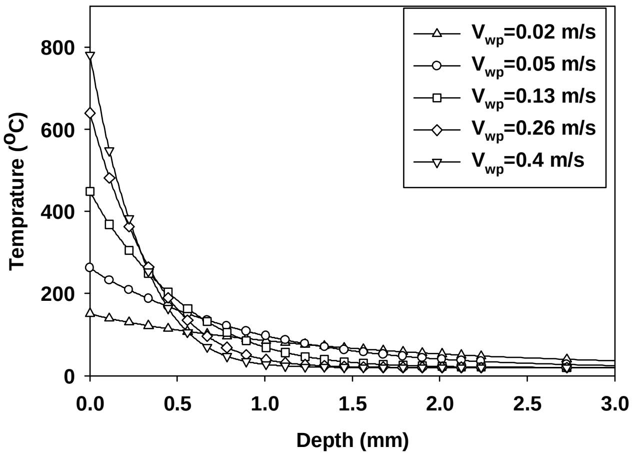

Fig. 4. Distribution of temperature in depth for different workpiece velocities.

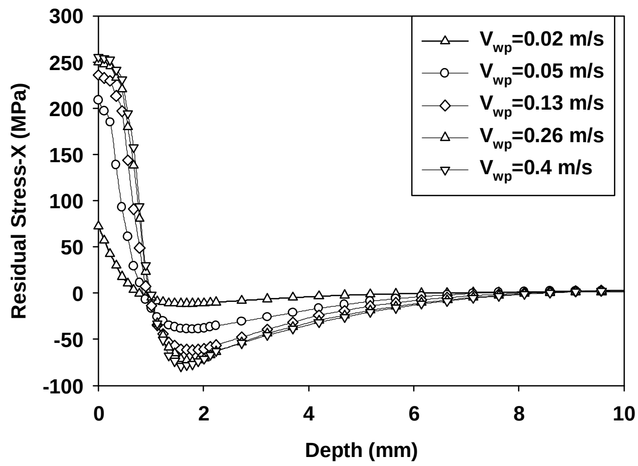

Fig. 5. Distribution of residual stress in depth for different workpiece velocities.

After obtaining temperature history of work material, mechanical analysis was carried out to investigate how depth of cut can affect development of residual stress. Fig. 7 shows residual stress induced by grinding as a function of depth of cut. The manner that depth of cut affects pattern of residual

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stress is different from workpiece velocity. Depth of cut did not have any pronounce effect on surface tensile residual stress. However, depth of tensile residual stress is highly sensitive to amount of cutting. Higher feed results in higher depth of tensile residual stress which can be very detrimental in fatigue and corrosion strength of ground component

C. Effect of Coolant

Further study examined the effect of coolant on temperature and residual stress field of grinding process. Coolant effect was exerted into the model by different heat convection coefficient: *15, 1000* and *20000* $W/m^{2o}C$. Depths of cut and workpiece velocity were *0.02 mm* and *0.13 m/s*, respectively.

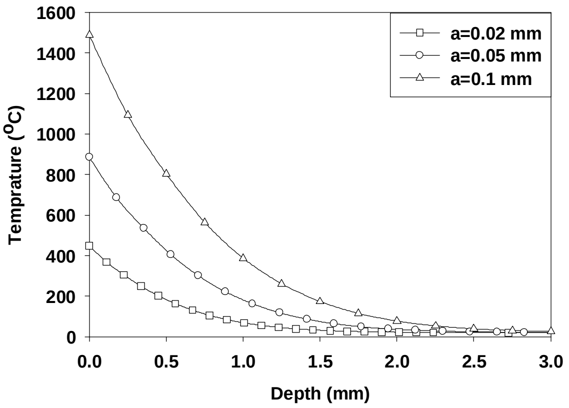

Fig. 6. Distribution of temperature in depth for different depths of cut.

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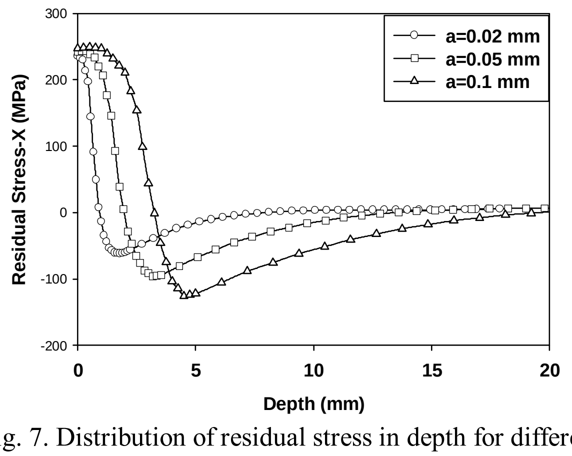

Fig. 7. Distribution of residual stress in depth for different depths of cut.

In depth temperature distribution in the middle of the workpiece, when heat flux reaches to that point, is shown in Fig. 8. Results show that different coolant types have not any considerable effect on maximum temperature which any point experiences during grinding. For analysing exact effect of coolant type, the time history of a surface node that placed on the middle of the surface is shown in Fig. 9 for different heat convection coefficient. It can be concluded from these results that the main influence of using coolant with higher heat convection coefficient is not decreasing temperature but providing a shorter time for temperature to cool down. However, if cooling time is less than a critical time, phase transformation will take place. From thermal point of view, more studies are needed to determine if higher convection coefficient is beneficial or detrimental.

Fig. 10 shows the effect of different heat convection coefficient in development of in depth residual stress in ground component. Calculations show higher heat convection coefficient can decrease surface residual stress very slightly.

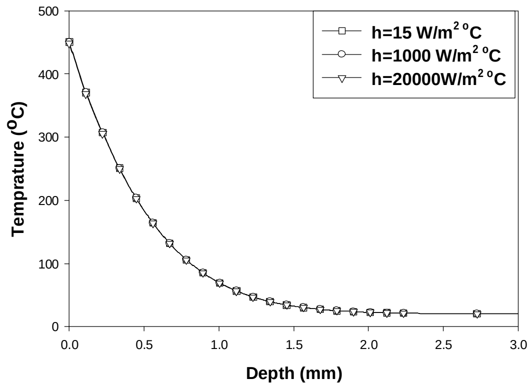

Fig. 8. Distribution of temperature in depth for different coolants.

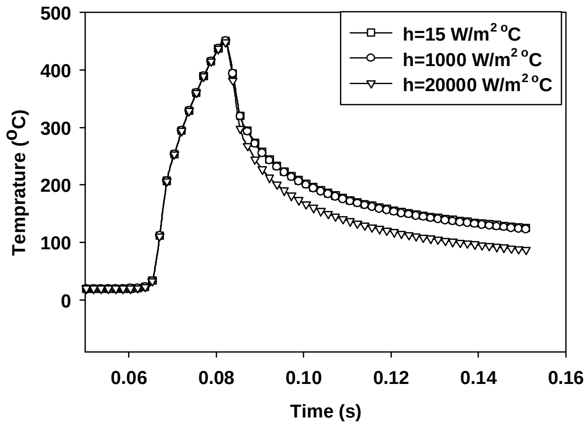

Fig. 9. Time history of surface temperature.

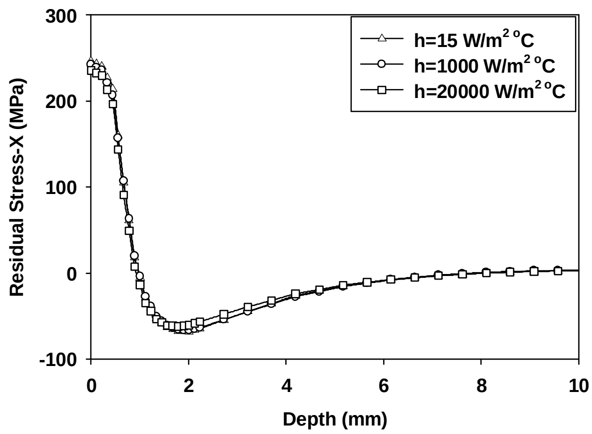

Fig. 10. Distribution of residual stress in depth for different coolants.

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VI. CONCLUSION

Finite element modeling of grinding process was carried out. By altering the grinding parameters such as depth of cut, coolant parameter and workpiece velocity, different grinding conditions were simulated. Results of parametric study presented in this work indicate, by carefully selecting the grinding parameters, minimum thermal and mechanical damage can be achieved. Also the following conclusions can be made:

- Higher workpiece velocities produce higher surface residual stress. However, depth of tensile residual stress is not sensitive to workpiece velocity.
- With increasing depth of cut, depth of tensile residual stress increases. However, surface residual stress remains nearly constant.
- Convection heat coefficient does not have any considerable effect on surface residual stress.

References

[1] M. Mahdi, L. Zhang, "Applied mechanics in grinding--VI. Residual stresses and surface hardening by coupled thermo-plasticity and phase transformation," *International Journal of Machine Tools and Manufacture*, vol. 38, 1998, pp. 1289-1304.

[2] M . Mahdi, L. Zhang, "Applied mechanics in grinding. Part 7: residual stresses induced by the full coupling of mechanical deformation, thermal deformation and phase transformation," *International Journal of Machine Tools and Manufacture*, vol. 39, 1999, pp. 1285-1298.

[3] A.G. Mamalis, J. Kundra´k, D.E. Manolakos, K. Gya´ni, A. Markopoulos, "Thermal Modelling of Surface Grinding Using Implicit Finite Element Techniques," *International Journal of Advanced Manufacturing Technology*, vol. 21, 2003, pp. 929–934.

[4] P.N. Moulik, H.T.Y. Yang, S. Chandrasekar, "Simulation of thermal stresses due to grinding," *International Journal of Mechanical Sciences*, vol. 43, 2001, pp. 831-851.

[5] X.X. Yu, W.S. Lau, "A finite-element analysis of residual stress in stretch grinding," *Journal of Materials Processing Technology*, vol. 94, 1999, pp. 13-22.

[6] D. Anderson, A. Warkentin, R. Bauer, "Experimental validation of numerical thermal models for dry grinding," *Journal of Materials Processing Technology*, vol. 204, 2008, pp. 269-278.

[7] D. Anderson, A. Warkentin, R. Bauer, "Comparison of numerically and analytically predicted contact temperatures in shallow and deep dry grinding with infrared measurements," *International Journal of Machine Tools and Manufacture*, vol. 48, 2008, pp. 320-328.

[8] H. Hamdi, H. Zahouani, J-M. Bergheau, "Residual stresses computation in a grinding process," *Journal of Materials Processing Technology*, vol. 147, 2004, pp. 277-285.

[9] M. Mahdi, L. Zhang, "A numerical algorithm for the full coupling of mechanical deformation, thermal deformation and phase transformation in surface grinding," *Computational Mechanics*, vol. 26, 2000, pp. 148-156.

[10] J. Zhang, P. Ge, T-C. Jen, L. Zhang, "Experimental and numerical studies of AISI1020 steel in grind-hardening," *International Journal of Heat and Mass Transfer*, vol. 52, 2009, pp. 787-795.