13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

Thermal Aspects of Environmentally Friendly-MQL grinding Process

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Abstract

This study attempts to quantify the amount of heat that goes into the workpiece during grinding processes. A new two dimensional transient heat conduction finite element model (FEM) has been made for both the conventional and environmentally friendly-MQL grinding processes. The boundary conditions for this problem were established based on the results of the heat transfer studies on semi-infinite bodies with a heat source moving on its surface. The model also takes into account the convective cooling of the grinding fluid/MQL. Hence this model can be used to evaluate the cooling effectiveness of various coolant-lubricant conditions based upon their convective heat transfer coefficient and bulk temperature. The finite element results can be used to evaluate the energy partition, which is defined as the fraction of total grinding energy that goes as heat into the workpiece. These results when matched with the experimental data give the energy partition. Results show that the finite element results match well with the experimental data.

Keywords: Environmentally friendly grinding, MQL, Thermal analysis, Temperature, FEM, Heat partition, Convection, Conduction

1. Main text

Green engineering is used to indicate environmental concerns in engineering. Green manufacturing is a subset of green engineering. Environmentally friendly machining is a part of green manufacturing (Fig. 1). In other words, green engineering is the design, commercialization, and use of processes and products which are feasible and economical while minimizing generation of pollution at the source and risk to human health and the environment [1-9]. Sustainable manufacturing considers environmental, economic, and social aspects (Fig. 2). The aim of the sustainable manufacturing is to develop technologies for transforming materials with objectives of reducing emission of greenhouse gases, avoiding use of nonrenewable or toxic materials, reducing the noise, and avoiding generation of waste. Environmentally conscious manufacturing is concerned with developing methods for manufacturing new product from conceptual design to final delivery and ultimately to the end-of-life disposal such that environmental standards and requirements are satisfied [7,9].

Generally, in different machining processes, offensive pollutants and by-products are generated which should be treated properly to protect the environment [7-9]. Many a times, a cutting fluid is used in machining to enhance the tool life and/or improve the surface integrity (Fig. 3). The fluids that are used to lubricate in machining contain environmentally harmful or potentially damaging chemical constituents. Prolonged exposure to coolants during machining may lead to respiratory irritation, asthma, pneumonia, dermatitis, cancer, etc. The disposal of petroleum-based oils is problematic. They cause surface water and ground water contamination, air pollution, and soil pollution. Nowadays research is going on to use vegetable-based oils as cutting fluids [9].

Apart from eliminating or minimizing the dangerous cutting fluids in machining, minimizing of energy consumption should be another objective of environmentally conscious machining (Fig. 4). This is because energy consumption is linked with environmental pollution, since almost all energy-generating methods pollute the environment in some way. This calls for the optimization of machining processes. Thus, optimization of machining processes is a must for an environmentally friendly machining process [7]. In many machining processes, the cutting tools are not utilized.
properly and are thrown away before their life is over. Moreover, a non-optimized machining process causes more tool wear and consequently increased consumption of cutting tools. Increased consumption of tool increases the expenditure due to procurement of tools as well as causes problems related to disposal of the tool (Fig. 4).

Grinding is mostly a final process on the workpiece that the dimensional and form accuracy as well as surface quality is very important. Heat associated with the energy expended by grinding is transported away from the grinding zone by the workpiece, the grinding fluid, the grinding chips and the grinding wheel.

It must be noted that during grinding operation, without using sufficient coolant-lubricant, thermal damage and dimensional inaccuracy on the workpiece surface will be generated and the methods of minimum grinding fluids or dry grinding have not yet been fully successful in industrial applications (Fig. 5). So in dry grinding, as therefore is no cutting fluid to transfer the heat from the contact zone, problems frequently occur in terms of thermal damage on the workpiece surface, increasing the grinding energy and grinding forces, wear of grinding wheel, low material removal rate (regarding relatively low depths of cut) as well as poor surface integrity compared to conventional flood grinding.

Many attempts have been made to reduce the coolant consumption in machining processes by different researchers (Fig. 6). In addition, previous results indicate that for environmentally friendly machining, the research focus has to be in: developing new cutting fluids, developing cutting tools, developing machine tools, optimization of machining process, development of environmentally-friendly workpiece materials.

Fig. 4. Environmentally friendly (sustainable) machining.

Fig. 5. Disadvantages of dry machining.

Fig. 6. Some technical solutions to use dry machining processes from cooling and lubricating stand points.

Fig. 7 shows a schematic of different strategies and methods employed to reduce the coolant consumption in
grinding. One attractive alternative for dry grinding is environmentally friendly-MQL grinding. This process uses a minimum quantity of lubrication and is referred to as near dry grinding [10]. In minimum quantity lubrication (MQL) grinding, an air-oil mixture called an aerosol is fed onto the machining zone. In MQL process, aerosols are oil droplets dispersed in a jet of air, oil droplets carried by the air fly directly to the tool working zone, providing the needed cooling and lubricating actions (Fig. 8). Immediately after leaving the nozzle hole, the jet starts to break up into a conical spray (spray cone angle ($\phi$) in Fig. 8) that is more and more diluted downstream the nozzle. Most of the oil mass and larger drops are concentrated near the spray axis, while the outer spray regions contain less oil mass and smaller drops. Consequently, droplet velocities are maximal at the spray axis and decrease in the radial direction due to interaction with the surrounding air. However, it was found that the effective MQL spray angle ($\phi_{eff}$) is $10^{\circ}$-$12^{\circ}$ of the spray cone angle ($\phi$) around the spray axis, at flow rate of 90 ml/h and 6 psi air pressure [3]. Within the spray angle of approximately $10^{\circ}$-$12^{\circ}$, multiple droplets have been agglomerated. This effect must be considered in positioning of oil mist spray nozzle in MQL machining processes [11].

Fig. 7. (a) methods for minimizing the use of grinding fluid, (b) special structuring provided by a dressing and conditioning process to reduce contact layer in dry grinding, (c) comparison of the conventional and different laser structured grinding wheels for dry grinding process, (d) T-Tool profile and an example of geometry of the segments in T-Tool profile to use in dry and minimal coolant grinding processes [15].

To prevent damage to the workpiece a thorough understanding of the grinding process is required, which can only be accomplished through experimental testing and process modeling. A considerable research effort has devoted to both theoretical and experimental aspects of heat transfer in grinding. The classic thermal analysis of moving heat source and the temperature at sliding contacts was studied by Jaeger [12]. The application of Jaeger’s moving heat source solutions to heat transfer problems in grinding was first proposed by Outwater and Shaw [13], whereby the grinding zone is approximated as a band source of heat moving along the surface of the workpiece. There has been significant work on individual modeling techniques reported in [6, 14, 15]; however, there has been a lack of experimental validation using common temperature measurement techniques [2]. Therefore, the focus of this work is to compare the contact temperatures obtained from validated numerical thermal models to the contact temperatures obtained from an analytical thermal model. Numerical modeling has been widely employed to simulate the workpiece grinding temperature for both 2D and 3D cases and further developed to analyze the phase transformation and thermal stress on ground surface. The FE models reviewed can be sub-divided in to four model types [16]. Thermal models can predict the temperature distribution within the workpiece whereas structural models can determine the mechanical deformations and resulting stresses. Thermal-structural models, or coupled models, can determine the resulting total stress from both thermal and mechanical loads. Ceramic models are treated in this work as a separate category from the thermal or structural analyses because of their fundamental difference in material removal mechanisms: initiation, coalescence, and propagation of microcracks. Malkin and Guo [2] and Biermann and Schneider [17] performed some of the earlier numerical studies to predict the transient temperatures during grinding.

Fig. 8. Schematic illustration of (a) MQL spray $\phi_{eff}=10^{\circ}$-$12^{\circ}$, (b) 3D image analysis of droplets on the surface, (c) distribution of MQL oil droplets on the target surface.
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MQL/fluid-workpiece convective heat flux effects outside the grinding zone, will be made to the existing thermal model. The effects of MQL technique such as air pressure, oil mist flow rate, and oil droplet properties will be considered in Nusselt number to predict convection coefficient of MQL grinding process. Using this analytical analysis procedure, the surface heat flux profile in the grinding zone as well as sub surface temperature distribution can be computed from grinding process parameters. It also must be considered to study the transient heat transfer and temperature distributions in workpiece with finite dimension and various boundary conditions. The model will be first validated by comparing with the traditional grinding thermal model assuming semi-infinite workpiece and experimental results from fluid, MQL and dry grinding processes. Effects of grinding position on the workpiece surface will further investigated using the FE model. When the workpiece is short transient heat transfer becomes more dominant during grinding. Investigation of grinding position effects revealed that the location of contact zone has a significant effect on the distribution of temperature in the workpiece.

2. Thermal modeling

The heat sources during grinding are from three locations: the abrasive grain/workpiece interface; the abrasive grain/chip interface; and the shear plane between the workpiece and the chip. The two mechanisms of heat generated are friction (at the grain/workpiece and grain/chip interface) and plastic deformation (at the shear plane and at the grain/workpiece interface due to planning). The heat generated in the grinding zone during MQL grinding is transferred into the chip, the oil mist, the wheel, and the workpiece (Figs. 9 and 10). In the model, heat will be assumed to be generated at the wheel-workpiece interface (global scale) and in the grain wear flat-workpiece interface (local scale). The average heat flux in the contact zone can be expressed as [2]:

\[ q_{total} = \frac{FV}{b} \]  

2.1. Analytical thermal modelling

The temperatures generated at the contact zone can be calculated by considering the contact zone as a band source of heat with the length of \( l_c \) which moves along the surface of the workpiece at the workpiece velocity \( V_f \). For this purpose, the quasi-steady state moving heat source model was used to calculate the temperature distribution within the workpiece. This model assumes two dimensional heat transfers in the \( x-z \) plane with either a triangular or uniform rectangular heat source distribution on the workpiece surface along the contact zone. While both models predict only slight differences for the same average heat flux at the contact zone, the temperature response with the triangular distribution has been found to be more consistent with measured temperature profiles. For this moving heat source model, the temperature rise in the workpiece is given by Equation (2) [2, 8]:

\[ T_w(x, z) = \frac{q_{total}}{2K_0} \int e^{-\frac{V_f (x-z)}{2K_0}} \left\{ \frac{V_f^2}{2K_0} \left( x-a \right)^2 + z^2 \right\} \cdot f(a) \, da \]  

where \( q_{total} \) is the heat flux that remains in the workpiece in which the heat partition to the workpiece background from the total heat flux can be expressed as [19]:

\[ R_{wb} = \frac{q_{work}}{q_{total}} \]  

(Fig. 10) and \( f(a) = 1 + \left( \frac{2a}{l_c} \right) \) for triangular heat source distribution, for uniform rectangular heat source distribution \( f(a) = 1 \), and \( K_0 \) is the modified Bessel function of the second kind of order zero.

The variation and calculation of convection heat transfer coefficients in the leading edge \( (h_{leading} = h_a) \), contact zone \( (h_{contact}) \) and trailing edge \( (h_{trailing} = h_b) \) are calculated from the derived equations and methodology explained in [8, 19].

Fig. 9. Illustration of the heat flux partitioning in the contact zone.

Fig. 10. Schematic diagram of heat flux partitioning during grinding process.

Fig. 11. FEM thermal model.

Fig. 12. Mesh generation for FEM thermal model; (a) workpiece dimensions, (b,c) magnification to show the mesh details.
Fig. 13. Temperature distribution under MQL (4) conditions, when; (a) \( t=0.3 \) s, (b) \( t=1.8 \) s, (c) \( t=2.1 \) s, (d) \( t=8 \) s.

Fig. 14. Maximum temperature rise versus the depth \( z \) by FEM model.

2.2. Finite element modelling

As explained in the previous sections, energy partition can be obtained by a method called temperature matching. The theoretical temperature distribution is obtained by assuming that the whole of grinding energy (power) converts to the heat flux in the contact zone [8]. These temperatures are then multiplied by the energy partition and matched with the experimental data as explained in [2, 16]. The problem to be analyzed is a two dimensional transient heat conduction problem. Therefore the geometry can be simplified to a rectangular block in the \( x-z \) coordinate system as shown in Fig. 11. During grinding process the workpiece is moving relative to the grinding wheel with a workpiece velocity \( V_{ft} \). This is equivalent to a heat source of intensity \( q_{workb} \) moving on the top of stationary workpiece with speed \( V_{ft} \). Here it is assumed that the heat source is uniform which is a reasonable assumption. The grinding fluid is applied only on one side of the wheel (leading edge, \( h_a \)). Thus as the heat source moves forward, the exposed surface is subjected to convective cooling of the grinding fluid. On the right side of the wheel the workpiece surface is exposed to convection heat transfer of trailing edge (\( h_b \)). Therefore the problem is to calculate the temperature history with a moving load (heat flux) and a time dependent convective cooling applied on the top surface.

The model was built by defining nodes and elements in ANSYS. The advantage of such a finite element model over a solid model is that, it helps to program the load stepping macros. This could be easily realized in the input code while writing the DO loops. Another advantage is that the reduced analyses loads can be applied at the master nodes. The element type selected was PLANE55 which is a four nodes two dimensional thermal element. This element was chosen mainly because it supports the mass transport option. At any instant the load is applied only on a part of the workpiece. It is evident that the temperatures near the load are subject to more change than the areas away from the load source. Hence a finer mesh is required near the heat source region and a coarser mesh could be used at other areas. This being a transient problem, the load moves with respect to time [20].

Fig. 15. Effect of cooling in the leading edge on surface temperature with \( F_t=18N \) and \( \Delta T=0 \).

Fig. 16. Effect of cooling in the trailing edge on surface temperature with \( F_t=18N \).

The meshes near the load are needed to be regenerated after every load steps and also the temperatures corresponding to the previous load step has to be transferred to the next time step as the initial condition for the next load step. This kind of dynamic meshing was not possible in ANSYS. Therefore a uniform mesh was considered. The mesh is as shown in Fig. 12. The elements are uniformly spaced along the \( x \) axis but unevenly along the \( z \) axis for the above mentioned reason (near the heat source and the workpiece surface, the elements with dimensions of 30 \( \mu \)m \( \times 0.5 \) mm and after distance 0.72 mm in \( z \) direction from the surface elements with larger sizes have been used.). Due to high temperature changes a lot in the grinding zone from the leading edge to the trailing edge, it is necessary to have more elements in the grinding zone. All the nodes and elements are numbered in a fixed pattern which later helps apply the surface load (heat flux and convection) on any given element face [20].
3. Materials and methods

In the previous study [6] an investigation was reported of the temperature and energy partition in grinding with minimum quantity lubrication (MQL) technique. Tests were performed in the down mode with parameters explained in [6]. Temperature distributions were determined in the subsurface of a hardened 100Cr6 steel workpieces through measuring by means of an embedded thermocouple during grinding in dry, MQL, and fluid environments. For each workpiece, about 40-45 grinding passes were required to grind the thermocouple tip depending on the position of the thermocouple tip in the hole. The depth beneath the surface was estimated for each pass as the product of the number of passes before the final one and the wheel depth of cut. The experiments were carried out with resin bond CBN wheels. The energy partition to the workpiece was estimated using temperature matching.

4. Results and discussion

Table 1 shows the experimental and calculated maximum surface temperature rise and energy partition ratio using temperature matching method to analyze the experimental results [6,8]. It can be seen that the maximum temperatures are not greatly different for the two flux distributions (uniform heat flux used for FEM and triangular heat flux applied for analytical model) with the experimental results. The main difference is the position of the maximum temperatures relative to the position of the center of the contact zone. For the uniform heat flux, the maximum temperature occurs at the trailing edge of the contact zone at high values of Peclet number, typical of grinding. For the triangular heat flux, the maximum temperature occurs at the midpoint of the band. This point has significance for the correct interpretation of measured temperature signals. For a uniform flux, the contact length is equal to the distance from the initial contact to the maximum temperature position. For a triangular heat flux, the contact length, l, is twice the distance from the initial contact to the maximum temperature position [15]. Fig 13a is the temperature results after load step 21, when the wheel is approximately in the beginning of the contact with the workpiece. Fig. 13a shows the temperature distribution within the workpiece. The transient nature is easily seen. Fig. 13b is the temperature results after 121 load steps, i.e. when the wheel is approximately in the middle of the workpiece. It can be seen that the maximum temperature occurs at the trailing edge, but there is no temperature rise from the ambient after the trailing edge. This could be attributed to the large Peclet number as the heat source is moving at high speed. There is not enough time for heat to conduct in the x-direction. Fig. 13c shows the plot of temperature distribution in the workpiece when the wheel is about to leave the workpiece. Maximum temperature occur when the wheel is about to leave the contact with the workpiece. Fig. 13d plots temperature versus depth at x=60 mm. It can be seen that the temperature inside the workpiece is higher than that on the surface. This is because of convective cooling on the top surface by h₀ and free air boundary conditions. During grinding the thermocouples measure the temperatures at a certain distance, z, below the workpiece surface. Temperature distribution on the surface and subsurface of the workpiece by FEM thermal model in Fig. 14 shows that the peak temperature rise for each successive grinding pass progressively increases until the thermocouple tip is ground.

Table 1. Results of temperature measurement experiments and simulation when grinding with CBN wheel.

<table>
<thead>
<tr>
<th>Test</th>
<th>F (N)</th>
<th>Rₑₑₑ</th>
<th>q_th (w/m²)</th>
<th>T_max (°C) (FEM model)</th>
<th>T_max (°C) (experimental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry</td>
<td>18</td>
<td>0.52</td>
<td>3.2188x10⁶</td>
<td>120</td>
<td>136</td>
</tr>
<tr>
<td>MQL</td>
<td>16</td>
<td>0.48</td>
<td>2.7765x10⁶</td>
<td>104</td>
<td>115</td>
</tr>
<tr>
<td>fluid</td>
<td>15</td>
<td>0.46</td>
<td>2.6533x10⁶</td>
<td>99</td>
<td>109</td>
</tr>
</tbody>
</table>

According to Fig. 15 and [8], cooling effect in the leading edge is negligible. By matching the measured temperature profile to the calculated temperature from the analytical heat transfer model, the convection heat transfer coefficient within the grinding zone (h₀_mol) and the trailing edge (h₀_trailing) can be found [6]. The convection heat transfer coefficient in the contact zone is much higher than that in the trailing edge for all cases. This is expected because of the much higher fluid velocity in the contact zone. Fluid grinding has much higher convection heat transfer coefficient than MQL grinding both in the contact zone and the trailing edge. The level of heat generated during grinding depends not only on the interaction forces within the grinding zone but also on the plastic deformation mechanism associated with the material removal processes. Consequently, the work material temperature rises to a level governed by the thermal properties of the work material and the grinding conditions. As the workpiece moves with workpiece speed, the grinding temperature starts to decrease due to the cooling effect and thermal energy diffusion into the work material. As a result, the work material experiences complex thermal strains and stresses the level of which may result in critical effective stresses above which the work material may undergo plastic deformation. In addition, for MQL grinding, the convection heat transfer coefficient in the trailing edge may not be uniform. The calculated temperature profile with a calculated h₀_trailing, approximately matches with the experimental measurement in the trailing edge near the contact zone, but not in the trailing edge far away from the contact zone, while the calculated temperature profile with a zero h₀_trailing has the opposite result. It indicated that MQL only provided some cooling in the trailing edge near the contact zone [6, 8]. This is probably due to the low flow rate in MQL grinding which only allows a small portion of the fluid to pass through the grinding zone.
and cool the nearby trailing edge of the ground surface; however, in the trailing edge far away from the contact zone, MQL provides no cooling. By imposing different values of convection heat transfer coefficients in the trailing edge and adiabatic in the leading edge and contact zone, the steady-state workpiece surface temperature profiles is shown in Fig. 16. Cooling in the trailing edge has a significant impact on the temperature profile. But it only influences the trailing edge, not the contact zone or the leading edge. The peak temperature remains about the same as that with high convection heat transfer values in trailing edge cooling. Fig. 16 shows the surface temperature profiles under the low and high values of $h_{\text{cooling}}$ with different initial temperatures of MQL/fluid. The results indicate that the initial temperature of MQL/fluid has strong effects on the heat transfer phenomenon in the grinding process when the convection heat transfer coefficient of MQL/fluid is high. On the contrary, Fig. 14 implies that the MQL coolant-lubricant type does not influence considerably on the grinding temperature. This can be explained by the results obtained from [4, 5] which demonstrate the negligible effects of the MQL coolant-lubricant types on the grinding forces when applying CBN wheels.

5. Conclusions

The MQL grinding performance was investigated and compared to dry and fluid grinding processes in terms of temperature distribution on the surface and subsurface temperature of the workpiece. A novel numerical method using a verified thermal model has been developed that provides a link between the analytical thermal modelling, experimental process parameters, and the corresponding numerically predicted temperatures. The numerical models were validated using data acquired from an embedded thermocouple system into the subsurface of the workpiece and were then compared to an established analytical contact zone thermal model. Based on the results of the experimental and theoretical investigations, the following conclusions for MQL grinding can be drawn:

- A good understanding of the process can be realized with the finite element model. Maximum temperature occurs when the wheel is about to leave the contact with the workpiece. In addition, when the wheel completely leaves the contact zone, the temperature inside the workpiece is higher than that on the surface. This is because of convective cooling on the top surface by $h_{c}$ and free air boundary conditions.
- The investigations on MQL indicate that despite the good lubrication of this technique in grinding process, it cannot meet the grinding cooling requirements comparing with fluid grinding with regard to the temperature response curves obtained in the analytical modelling and the experiments carried out with MQL. This is the main reason limiting the widespread application of MQL in grinding.
- In order to better understand the heat transfer and temperature distributions in workpiece, the convection heat transfer coefficient within the contact zone ($h_{\text{contact}}$) has been found by matching the measured temperature profile to the calculated temperature profile. By considering the difference between the $h_{\text{contact}}$ values of MQL and grinding fluids (1500 and 45000 W/m²K for MQL and fluid, respectively), and the calculated energy partition ratio for MQL and fluid grinding, it can be proved that the same temperature rise at the contact zone is resulted when the MQL grinding tangential force is 40–50% of that in fluid grinding.

References

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