Numerical Stress Analysis of Creep-Feed Grinding Through Finite Element Method in Inconel Alloy X-750

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Finite Element Method
Inconel X-750

\section{1. Introduction}

Among the processes are used in abrasive machining, creep-feed grinding process is of particular interest due to some benefits like increased material removal, surface quality and good dimensional accuracies which is common in manufacture of aerospace industries components \cite{1, 2}. However the noticeable residual stress that creep-feed grinding as an efficient and highly accurate machining process adds to the components is an obsession for designers. On the one hand the shortage of knowledge of design engineers and on the other hand the high cost of experimental residual stresses measurement systems like X-ray or Neutron diffractions has triggered to weak performance of grinded structures. Surface quality is known as the important criteria for assessing the geometric characteristics, physical–mechanical performance and usability, life and reliability of mechanical parts among designers. In order to reach a good surface quality controlled-stress creep-feed grinding is a necessity. For controlling of stresses generated by grinding processes, the perception of their creation elements is a need. Designers always tend to diminish the undesirable residual stresses in grinded components with an appreciate choice of grinding parameters like cutting depth, feed rate, wheel speed, cooling system, grinding wheel type etc. This could be obtained best in case the designer has a dependable model for predicting of grinding events. However the experimental data as a strong tool is essential to give assurance to model. The first plan to predict residual stress generated by grinding process is an analytical model. Some researchers \cite{3-5} investigated the workpiece temperature in this way but complexity of process has caused some difficulties in extracting of equations for calculating the grinding parameters.

Numerical simulation is another way to predict residual stresses by using mathematical models, programming and finite element analysis software that provides fine precious. Despite of all merits, at the moment the shape of thermal loading profile has been accompanied with some challenges. Researchers have presented differing profiles for thermal and mechanical loadings \cite{6-10} which indicate different performance respect to sort of grinding. They reported the triangular heat source models (scalene and following that right-angled) are closer to experimentally temperature graphs in creep-feed grinding process. It is remarkable the simulation of creep-feed grinding due to high cutting depth, contact angle and temperature gradient has been gone along with some controversies. The first point should be notice is...
workpiece geometry (simple or complex), the ratio of wheel radius to contact length and finally the ratio of wheel thickness to workpiece width. In fact for simple geometries, great ratio of wheel radius to contact length and when wheel thickness is greater than workpiece width, the 2D model is proposed. The second point is Peclet number and contact angle parameters. D. Wang et al. reported that for lower Peclet numbers using of right-angled triangular heat flux with error range of 4.2% to 11.6% are appropriate to predict grinding temperature [5, 11].

In this study, an appropriate 2D finite element model was developed using ABAQUS software to simulate the residual stresses distribution of Inconel X-750 generated by creep-feed grinding process. In order to study the cooling effect on residual stress and workpiece temperature, grinding process was done in dry and flood modes. The influence of coolant was expressed with coefficient of thermal convection. Fully-coupled mechanical-thermal analysis was used to determine the residual stresses. Finally the residual stresses are measured by using electro polishing layer removal technique to validate finite element analysis.

2. Numerical Simulation

2.1. Principle

Figure 1 illustrates the schematic of creep-feed grinding process. Grinding wheel with diameter rotates on its axis with \( v_c \) linear speed. Cutting depth and feed rate of workpiece are \( a \) and \( v_w \), respectively. The contact length between workpiece surface and grinding wheel is \( L_c \). Numerical simulation of process requires a comprehensive technical knowledge of geometry, thermal-mechanical properties, initial and boundary conditions and loading statue. The microscopic events and reactions between wheel and workpiece in contact area are ignored and simulation is just done at macroscopic dimensions. The proposed model is an approximation of the events and reactions of contact between the wheel and the workpiece. In fact grinding wheel is removed physically and its effects are considered. It means the mechanical and heat effects of wheel are expressed as a combination of normal and tangential forces and a moving heat source. The heat generated by small chips is also disregarded to simply the analysis.

The phase transformation does not occur during temperature changes in Inconel X-750, so simulation only investigated the thermal and mechanical effects not residual stresses created by phase transformation. Numerical simulation was performed by using the Abaqus® / standard finite element software and DFLUX, DLOAD and UTRACLOAD subroutines. The analysis was done through two steps; firstly the top surface was exposed to the coupling of thermal and mechanical loadings, then is cooled until reached ambient temperature. The proposed model was validated by experimental data. Figure 2 shows the numerical simulation schema.

![Figure 1. Schematic sketch of creep-feed grinding process](image1)

![Figure 2. Flowchart in the determination of residual stresses in creep-feed grinding](image2)
2.2. Finite element analysis

2.2.1. Finite element mesh and material

As it is shown in figure 3 model is assumed as a two-dimensional plate with 95 mm length and 1.6 mm thickness. Element type of mesh is CPE4T (4-node plane strain thermally coupled quadrilateral bilinear displacement and temperature). Finite element mesh includes over 35640 elements and 36859 nodes. It is noticeable that these dimensions increase by moving across the depth. To reach an optimized mesh for analysis the iterative adaptive remeshing method was utilized. It was observed that after 35640 elements, stresses reach a constant amount that no considerable variations by increasing of element number observed. In fact a compromise between computation time and accuracy provided. It is remarkable that due to high temperature of grinding zone, physical and mechanical properties of Inconel X-750 in the simulation are considered as temperature dependent. The mechanical properties and chemical composition are given in table 1 and 2.

![Figure 3. Finite Element Mesh](image)

<table>
<thead>
<tr>
<th>Density (gr/cm³)</th>
<th>Modulus of Elasticity (KN/mm²)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (kJ/kg-K)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.276</td>
<td>213.7</td>
<td>12</td>
<td>0.43</td>
<td>979.1</td>
<td>1503.1</td>
</tr>
</tbody>
</table>

![Table 1. Mechanical properties of Inconel X-750 [12]](table)

<table>
<thead>
<tr>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Ti</th>
<th>Co</th>
<th>Mn</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 70%</td>
<td>14-17%</td>
<td>5.0-9.0%</td>
<td>2.25-2.75%</td>
<td>≤ 1.0%</td>
<td>≤ 1.0%</td>
<td>≤0.08%</td>
</tr>
</tbody>
</table>

![Table 2. Chemical composition (wt. %) of X-750 Inconel super alloy [12]](table)

2.2.2. Initial and boundary conditions

The initial temperature of the workpiece and coolant are assumed the room temperature i.e. 25 °C. The coolant effects have exerted as h (W/K m²) coefficient of thermal convection while are applied on the top and side walls uniformly. During the process the bottom surface is considered adiabatic and constrained in direction of x and y. Thermal and boundary conditions are shown in figure 4.

![Figure 4. Thermal and boundary conditions of model](image)
2.2.3. Determining the thermal convection coefficient

The coolant quantity is expressed with coefficient of thermal convection. This coefficient in the water-based coolant that water plays the cooling role is [13]:

\[ h = 0.739 \sqrt{\frac{v_c}{L_c}} \]  

\( v_c \) is the output velocity of the coolant in the nozzle.

2.2.4. Thermal loading model

In present study, the right-triangular heat source profile was used. Heat flux with \( V_w \) linear speed moves along the top surface in the direction of grinding. The contact length between grinding wheel and workpiece surface is obtained from following relation:

\[ L_c = \sqrt{a \cdot d_w} \]  

Heat flux distribution in contact area is as follows:

\[ q(x) = q_0 \left( 1 + \frac{2x}{L_c} \right) \]  

\( q_0 \) is the total heat input into the workpiece per length unit [W/mm]. Now with knowing the thermal model, it is necessary to determine the amount of heat input into the workpiece. This amount can be calculated from the following equation:

\[ q_0 = \eta \frac{F_t \cdot v_c}{L_c} \]  

The amount of \( \eta \) is expressed by Shaw and Blok's heat partition analysis as follows [14]:

\[ \eta = 1 - 0.45 \frac{u_{ch}}{u} \]  

\( u \) as the special grinding energy is calculated from below equation:

\[ u = \frac{F_t \cdot v_c}{a \cdot V_w} \]  

\( u_{ch} \) is the required energy for chip formation with amount of 13.8 j/mm³ for all ferrous materials [15].

2.2.5. Mechanical loading model

Mechanical loading of creep-feed grinding process includes of applying the normal and tangential forces into the grinding area. Normal stress and shear stress have elliptic distribution with magnitude of \( P_n \) (N/m²) and \( P_t \) (N/m²), respectively. In order to employ normal and shear stress DLOAD and UTRACLOAD subroutines were used. The elliptic distribution of mechanical stresses in the contact area are obtained as follows:

\[ P(X) = P_{nt} \sqrt{\left(1 - \frac{x^2}{a^2}\right)} \quad \frac{-L_c}{2} \leq x \leq \frac{L_c}{2} \]  

\( P_n \) and \( P_t \) are calculated from below equations:

\[ P_n = \frac{3F_N}{2\pi(L_c)^2}, \quad P_t = \frac{F_t}{\pi(L_c)^2} \]  

3. Experimental validation

In order to validate the residual stresses values obtained by numerical simulation, the experiments were performed. The specimen is Inconel X-750 super alloy steel with dimensions of 95 mm × 15 mm× 1.75 mm (length, width and thickness, respectively). In order to relieve the initial stresses, the specimens were subjected to temperature of 1149° C for 120 minutes. To reach the best mechanical properties the hardening process was also done. As shown in table 3 the grinding machine type of MST300 was used. An aluminum grinding wheel with dimensions of 250×20×76.2 (diameter, thickness and hole size respectively) and 32A46-G12VBE specification with 20.6 m/s linear speed was employed. The depth of cut is 150µm and specimen was mounted on the dynamometer while moves with linear speed of 1.6 mm/s. Flood grinding was done under the flow rate of 75.6 L/min. Figure 5 shows experiment setup. Measurement of non-
uniform residual stresses generated by creep-feed grinding was done through electro polishing layer removal technique that is called L.R.E.P briefly at the Analysis, Measurement, and Engineering of Residual Stress (AMERS) Research Lab. The basis of this method is measurement of deflection of the specimen in terms of the amount of the removed material and determining stress from the formulas. In fact the specimen is mounted on the holder and only the side front of the cathode is exposed to corrosion. The deflection is constantly measured using …laser sensor and analyze using dedicated software developed at AMERS research lab.

The profile of the residual stress in the removed layers is obtained from the device demonstrated in figure 6. This device consists three section: specimen mounting, electrolyte cooling and stabilizing, specimen deflection measurement and corrosion. As mentioned the specimen is mounted on the holder while parallel to the cathode with 20mm gap. The current density of 652 (A/m²) is provided to perform an electro polishing process. The cooling system keeps the temperature of electrolyte (25±1 °C) along with a small pump. The electrolyte includes of 10 ml HCL+5 ml HNO₃+ 85 ml ethanol (95%). The surface of the ground specimen with a certain length is solubilized using the electro polishing in the mentioned electrolyte. The remaining surfaces of specimen are protected from the corrosion by having insulation tape on them. As shown in figure 6 a measurement arm is mounted to the free end of specimen which makes it feasible to measures the deflection of specimen using laser sensor at a safe distance out of electrolyte. It should be notice that because of the rippling movement of electrolyte due to electric pump, the top end of specimen is coated with insulating tape to avoid from uncontrolled corrosion. Table 4 gives the information of process in short.

4. Results and discussion

Figure 7 shows the surface texture after the creep-feed grinding and electro polishing processes. As it could be observed the surface finish at conventional flood grinding is far better than dry grinding. It is undeniable that some visible cracks and burns are apparent in dry ground specimen. The most significant obsession in layer removal using electro chemical methods is uniform material removal in particular when the deflection measurement is continuous and specimen do not exit from the electrolyte during the process. Figure 7 also presents the surface quality after electro polishing process. As it could be seen low material removal rate and controlled-work of this study leads to uniform corrosion and removal of the layers from the surface.

<table>
<thead>
<tr>
<th>Table 3. Creep-feed grinding parameters</th>
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<tbody>
<tr>
<td>Grinding machine model</td>
</tr>
<tr>
<td>Grinding mode</td>
</tr>
<tr>
<td>Grinding wheel</td>
</tr>
<tr>
<td>Grinding liquid</td>
</tr>
<tr>
<td>Wheel speed Vs (m/s)</td>
</tr>
<tr>
<td>Feed rate Vw (mm/s)</td>
</tr>
<tr>
<td>Cutting depth a(μm)</td>
</tr>
<tr>
<td>Grinding fluid flow rate (L/min)</td>
</tr>
<tr>
<td>Coolant velocity at exit of nozzle (m/s)</td>
</tr>
</tbody>
</table>

Figure 5. Experimental setup: A) Grinding wheel, B) Dynamometer, C) Specimen, D) Nozzle
Table 4. Information of electro polishing layer removal process

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>10 ml HCL + 5 ml HNO₃ + 85 ml ethanol (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode material</td>
<td>Stainless steel 316</td>
</tr>
<tr>
<td>Anode material</td>
<td>X-750 Inconel super alloy</td>
</tr>
<tr>
<td>The ratio of area of the cathode to the anode</td>
<td>4 to 1</td>
</tr>
<tr>
<td>Electrolyte temperature (°C)</td>
<td>25</td>
</tr>
<tr>
<td>Current density (A/m²)</td>
<td>652</td>
</tr>
<tr>
<td>Distance between the cathode and anode (mm)</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 6. The scheme of electro polishing layer removal measurement system

Table 4. Information of electro polishing layer removal process

According to equation (1), the coefficient of thermal convection for 75.6 L/min flow rate was calculated of 11150 W/K m². This amount in dry grinding is assumed 15 W/K m². Figure 8 shows the temperature distribution from close view while heat flux is approaching the tail end of surface. As it could be observed, on the top (Figure 8a) the maximum temperature is approximately 649 °C in dry grinding. On the bottom (Figure 8b) temperature has significantly declined roughly 305 °C using coolant with 75.6 L/min flow rate. In fact the leap of convection coefficient to 1150 W/K m² has put considerable decreased impacts on the temperature history of specimen in that, the maximum temperature of specimen has been about 53% in decline compared to nonuse of coolant (the highest flow rate).

Figure 7. Visual photographs of specimens.

Spec A, After dry creep-feed grinding

Spec A, After layer removal process

Spec B, After flood creep-feed grinding

Spec B, After layer removal process

Figure 8. Temperature distribution of the numerical simulation: (a) Dry (h=15 W/K m²), (b) Flood (h=11150 W/K m²)
Figure 9 presents the simulated residual stresses profile in the depth beneath the surface of specimen after dry and flood grinding. Analysis of the simulated results points to noticeable changes in the residual stresses distribution along the depth depending on the coolants. Tensile residual stresses are dominate in both grinding modes, although the maximum stress has been in decline about 23% in flood creep-feed grinding. In the further zones from surface layers the tensile stresses turn into compressive. It is remarkable that regarding low amount of normal forces measured by dynamometer (41.3 N and 18.7 N in dry and flood grindings, respectively), the normal stress effects are about negligible and as residual stresses generated by phase transformation does not occur, hence the specimen stresses have thermal origin. These stresses approach to zero on the far side of surface. When analyzing the impacts of coolant on the maximum surface stresses it was observed that tensile stresses has sensible dropped from 914 MPa(dry) to 660 MPa(flood). The simulated results (Figure 10) provided the same outcomes with about 15% and 9% difference for dry and flood grinding, respectively. However according to figure 11 the maximum depth in which residual stresses were released after layer removal has fallen from 320 µm in dry grinding to 172.8 µm in flood grinding (46% reduction). These results vividly show the effects of coolant on the deposition depth.

Figure 9. Simulated residual stresses distribution along the depth of specimen after dry and flood grindings.

Figure 10. The chart of maximum values of surface residual stress after creep-feed grinding.

Figure 11. The chart of maximum values of residual stresses deposition obtained with experimental data.
Figure 12 compares $\sigma_{xx}$ residual stress distribution along the depth numerically and experimentally. Besides of provided graphs, the visual distribution of stresses near the surface has also presented. As it could be observed the results of thermal-mechanical coupling models give very interesting results for the simulating of creep-feed grinding. The difference between numerical and experimental results may be originated from some simplifications and assumptions of section 2. As the simulated results illustrated the temperature history generated by dry grinding is considerable higher than flood grinding that because of high friction between wheel grains and specimen and causes to created higher and deeper stresses. For instance the stress of 250 MPa is obtained at depth of about 260 µm in dry grinding whereas both measured and simulated data demonstrated 6.5 times lower depth at present of coolant.

**Figure 12. Experimental and numerical comparison of residual stresses: (a) Dry (h=15 W/K m²), (b) Flood (h=11150 W/K m²)**

5. Conclusions

This work offers an appropriate 2D model for predicting of residual stresses generated by creep-feed grinding. Due to non-existence of phase transformations in Inconel X-750, thermal and mechanical effects are only considered. The grinding normal and tangential forces were firstly obtained. Following that based on the grinding parameters and mentioned equations the residual stresses distribution simulated. The creep-feed grinding of Inconel X-750 experiments were performed to validate the proposed model. Due to negligible pressure stresses, the tensile stresses generated by thermal loading were dominated in the surface of workpiece in the way using the coolant caused a steep decline of these unwanted stresses. However, it should be notice that the assumptions of this study brought out some errors which mainly occurs near the surface.

References


