A comprehensive model of material removal mechanism (in lapping process) by single-grain scratch test

Praveen Sridhar, Driss Fares, Kristin de Payrebrune
Institute of Applied Structural Mechanics (asm)

- Lapping process characteristics
- Damage and FE material removal model
- Parameter study and results
- Conclusion
- Further steps
Lapping process characteristics

Basic models and coupling

- Damage and FE material removal model
- Operation parameter
- Structural parameters
- DEM grit kinematics model
- CFD lapping fluid model

Coupling relationships between the models.
Lapping process characteristics

Kinematics of grits
Lapping process characteristics

FE model of a single grit indentation

Important structural parameters
- grit geometry
- number of cutting edges
- material properties (ductile or brittle)

Important operational parameters
- sliding velocity
- applied force/depths of cut

Resulting parameters
- material removal
- surface roughness
- stress distribution
FEM Simulation - Framework

Workpiece-cutting tool model and boundary conditions

Tool material: rigid body (E = 2×10^5 MPa, ρ = 2800 kg/m³)
Workpiece material: aluminium alloy (A2024-T351; E = 71×10^3 MPa, ρ = 2700 kg/m³)

Tool Speed: 10 m/s

Simulations performed:
- Effect of tool geometries: Tool wedge angle β (10°-160° in steps of 30°)
- Effect of depth of cut (d_c): 0.25, 0.5, 0.75, 1, 1.25 mm.
Damage and FE material removal model

Johnson-Cooke Material Model

• Widely used in material flow stress model in metal machining simulations.

\[
\sigma = \left[ A + B(\varepsilon)^n \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_{room}}{T_{mel} - T_{room}} \right)^m \right]
\]

Where,
- \( f_1 \) - components describing strain hardening behaviour
- \( f_2 \) - components describing strain rate sensitivity behaviour
- \( f_3 \) - components describing thermal softening behaviour of the metal

• The effective von Mises stress \( (\sigma_f) \) is calculated as a compound of the above three components.

Damage and FE material removal model

Johnson-Cooke Failure Model

- The JC failure model is used in conjunction with the JC material model
- This model is suitable for high strain rate deformations such as high speed machining.
- The effective fracture strain $\bar{\varepsilon}^f$ is described by the following equation:

$$\bar{\varepsilon}^f = \left[ D_1 + D_2 \left( \frac{D_3 \sigma_m}{\bar{\sigma}} \right) \right] \left[ 1 + D_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right] \left[ 1 - D_5 \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right]$$

- The damage parameters for aluminum alloy (A2024-T351):

<table>
<thead>
<tr>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$D_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>0.13</td>
<td>-1.5</td>
<td>0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

Damage and FE material removal model

Damage initiation and damage evolution for alloy (A2024-T351)

- Stress-strain behaviour of a material undergoing damage according to Hillerborg fracture energy model

Criterion for damage initiation

\[ w = \sum \frac{\Delta \bar{\varepsilon}}{\bar{\varepsilon} - f} \]

Expression for the damage parameter

\[ D = \frac{L\bar{\varepsilon}^{pl}_{f}}{\bar{u}_{f}^{pl}} = \frac{\bar{u}^{pl}}{\bar{u}_{f}^{pl}} \]

Stress after damage initiation

\[ \sigma = (1 - D)\bar{\sigma} \]

Parameter study and results

Impact of grain geometry

- von Mises stress contours for tool wedge angle $\beta$ (10°-160° in steps of 30°)
Parameter study and results

Impact of depth of cut

- von Mises stress contours for varying depths of cut ($d_c$)
Parameter study and results

Impact Mean-stress vs Tool angle/ Depth of cut ($d_c$)

Tool angle

Depth of cut

Impact Mean-stress vs Tool angle/ Depth of cut ($d_c$)
Conclusion

- The physical force model was developed to simulate the material removal mechanisms for a single grain scratch test.
- The Johnson-Cooke material and damage model was used to simulate the damage mechanisms.
- Two sets of simulations were conducted:
  1. Changing the tool wedge angle $\beta$ (10°-160° in steps of 30°).
  2. Changing the depths of cut 0.25, 0.5, 0.75, 1, 1.25 mm.
- From the results it is clear that stresses increase with increase in the tool wedge angle as well as with increase in the depths of cut.
- Steep increase in the normal stresses with increase in tool wedge angle $\beta$.
- Higher tangential stresses compared to normal stresses with increase in the depths of cut ($d_c$).
Further Steps

• The representative material damage model is developed for single grit scratch tests, the model will be further developed for materials to be tested and validated in a laboratory environment

• Further improvements in the Johnson-Cooke model by using modified Johnson-Cooke models best suitable for the materials used in the experiments.

• Development of material damage model to simulate damage mechanisms in brittle materials

• Coupling of grit kinematics simulation (DEM) and fluid mechanic simulation (CFD) with the FEM simulation for overall understanding of the material removal mechanisms in the lapping process.

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