PROCESS OPTIMIZATION FOR MACHINING OF HARDENED STEEL MATERIALS

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Objective

Design the optimal *Tool Geometries* (edge preparation, rake angle and tool nose radius…) and *Cutting Conditions* (cutting speed, feedrate and DOC) to achieve the specified process performance goals with satisfactory surface finish (surface roughness, white layer thickness, residual stress distribution) and any other practical constraints, such as tool life, power consumption and the vibration stability…
Process Optimization Flow Chart

Analytical Model (Machine Mechanics)
- Temperature Model
- 3D Oblique Force Model
- Tool Wear Prediction

Intelligent Model (Artificial Neural Network)
- White Layer Thickness Prediction
- Residual Stress Distribution Prediction

Intermediate Outputs:
- Cutting Temperature, 3D Cutting Force
- Tool Wear Rate/Tool Wear
- White Layer Thickness, Surface Roughness
- Residual Stress Distribution

Optimization Block:
- Penalty Assignment
- Priority Mapping
- Search Engine

Functionality Outputs: Based on specified process performance goals
- Optimal cutting condition and tool geometry
- Tool life
- Surface Finish (white layer thickness, residual stress distribution, surface roughness)
- Cost per part & Cycle time per part
Optimization Block (MIEA)

- The genotype space is the same as phenotype space
- One-gene-one-variable scheme
- Binary implementation for integer (discrete) variables
- Float point implementation for continuous variables
- Tournament selection (tournament size q=8)
- Local fine turning capabilities
- A new penalty constraint handling method
- $\alpha \mu$ population initialization
Temperature Model 1

- Average Temperature along Rake face and Flank face vs. VB

\[
T_{rake\_ave} = T_0 + \Delta T_{sz} + \psi \Delta T_M + \Delta T_{VB}
\]

\[
\Delta T_{sz} = \frac{(1 - \beta) F_s V_s}{\rho C V_c a^* t^*}
\]

\[
\Delta T_c = \frac{F V_{chip}}{\rho C V_c a^* t^*}
\]

\[
\Delta T_{VB} = \frac{\Gamma q_{rubbing} VBw}{\rho C V_c a^* t^*}
\]

\[
\ln \left( \frac{\Delta T_M}{\Delta T_C} \right) = 0.06 - 0.195 \delta \left( \frac{R_T t_2}{h} \right)^{1/2} + 0.5 \ln \left( \frac{R_T t_2}{h} \right)
\]

\[
T_{rake\_ave} = T_{c\_ave}, \quad T_{flank\_ave} = \gamma T_{rake\_ave}, \quad T_{w\_ave} = T_{flank\_ave}
\]

\[
\beta = 0.5 - 0.35 \log_{10}(R_T \tan \phi) \quad \text{For } 0.04 \leq R_T \leq 10.0
\]

\[
\beta = 0.5 - 0.15 \log_{10}(R_T \tan \phi) \quad \text{For } R_T \geq 10.0
\]

\[
\Gamma = 0.4, \quad \gamma = 0.8 \quad \text{(Oxley, 1989; Boothroyd, 1963, 1967)}
\]
Temperature Model 2

- Maximum Tool Temperature along Flank face vs. VB

\[ \Psi = \frac{T_{\text{max_flank}}}{T_{\text{ave_flank}}} = k_1 V_c V B + k_2 \text{doc} / \text{feed} + k_3 \]

- \( V_c \): sfpm, \( V B \):um, \( \text{doc} \): inch, \( \text{feed} \): ipr

\[ k_1 = 1.11219 \times 10^{-6}, \]
\[ k_2 = 3.1906 \times 10^{-3}, \]
\[ k_3 = 999.3387 \times 10^{-3} \]
Force Model

Workpiece material property:

\[ \sigma = \left( A + B \varepsilon^n \right) \left( 1 + C \ln \frac{\varepsilon}{\varepsilon_0} \right) \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right) \]

- Johnson-Cook equation coefficient: A, B, C, m, n
- Specific heat capacity
- Thermal conductivity
- Density

Tool material property:
- Specific heat capacity
- Thermal conductivity
- Density
Hierarchical Model Scheme

Workpiece/Tool Material

Cutting Condition

Tool Geometry

Analytical Model
- Temperature model
- 3D oblique cutting force model

Temperature

Force

Analytical Model
Flank wear rate model

VB

Intelligent Model (Artificial Neural Network)

White Layer
Thickness

Residual Stress
Distribution

Experimental results of White layer formation

Experimental results of Residual stress distribution

Experimental Database
Flank Wear Prediction

\[ \frac{dVB}{dt} = \frac{(\cot \gamma + \tan \alpha)R}{VB(R - \tan \gamma)} \]

\[ \begin{align*}
K_{\text{abrasion}} K \left( \frac{P_a^{n-1}}{P_t^n} \right) V_c V_B \bar{\sigma} \\
+ K_{\text{adhesion}} e^{aT} V_c \bar{\sigma} \\
+ K_{\text{diff}} \sqrt{V_c V_B e} \frac{K_Q}{T+273}
\end{align*} \]

(Huang & Liang, 2002)
Intelligent Advisory System for Hard Turning Process

Version 2.1
PMRC, MaRC
The George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology

Designed by: Jing Ying Zhang
Process Optimization

Application:
- The inner ring OD hard turning
- Dry machining
- Material 52100(60~64HRC)
- Tool Insert KB5625
- Fixed Depth of Cut = 0.25 mm
Requirement

- Surface roughness is smaller than 0.5um
- No white Layer
- Compressive circumferential and longitudinal residual stress profiles
- Available power is smaller than 1.5HP
Design Variables

**Tool Geometry:**
- Nose Radius: 2, 3, 4 nose (*Discrete Variable*)
- Back rake angle: -5 degree, 0 degree, +5 degree (*Discrete Variable*)
- Clearance angle: 5, 8, 10, 12, 16, 20, 25, 30 degree (*Discrete Variable*)
- Chamfer angle: 0 degree, 15 degree, 20 degree (*Discrete Variable*)

**Cutting Conditions:**
- Cutting speed: $v_c$ (*Continuous Variable*)
- Feedrate: $f$ (*Continuous Variable*)
- The number of workpieces per insert: $N$ (*Integer*)
Constraints

300 \leq v_c \leq 600 \text{ (sfpm)}

0.002 \leq f \leq 0.006 \text{ (ipr)}

Surface Roughness: \quad R_a(k) \leq 0.5\text{um}

White Layer Thickness: \quad WL(k) \leq 0\text{um}

Longitudinal residual Stress: \quad \sigma_L(k) \leq 0

Circumferential residual Stress: \quad \sigma_R(k) \leq 0

Power: \quad P(k) \leq 1.5HP

k=1,2,...N
Objective Function

- **Minimum Cost per Part**

\[ C_p = (C_m' + C_w') t_t + \frac{C_t}{N} \]

- **Maximum Production Rate**

\[ t_t = t_{load} + \frac{t_{mach}}{f_{mach}} + \frac{t_{ct}}{N} \]

- **Both**

\[ Obj = w_p C_p + w_t t_t \quad (w_p = 0.5, w_t = 0.5) \] is used
## Optimal Results

### Minimum Cost per Part

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Radius</td>
<td>4 nose (1.588mm)</td>
</tr>
<tr>
<td>Back Rake Angle</td>
<td>-5</td>
</tr>
<tr>
<td>Chamfer Angle</td>
<td>-20</td>
</tr>
<tr>
<td>Clearance Angle</td>
<td>30</td>
</tr>
<tr>
<td>$N$</td>
<td>811</td>
</tr>
<tr>
<td>$v_c$ (sfpm)/(m/s)</td>
<td>600/ 3.0488</td>
</tr>
<tr>
<td>$f$ (ipr)/(mm)</td>
<td>0.006/0.1524</td>
</tr>
</tbody>
</table>
Optimal Results

<table>
<thead>
<tr>
<th>Process Output</th>
<th>Constrain Value</th>
<th>Total Cost ($/pc)</th>
<th>Cycle Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>VB (um)</td>
<td>213.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra (um)</td>
<td>0.4571</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WL(1) (um)</td>
<td>0</td>
<td>0.9116</td>
<td>0.8434</td>
</tr>
<tr>
<td>WL(N) (um)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRR(cm³/s)</td>
<td>11.6159</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Residual Stress Profile:

Circumferential Residual Stress Profile

Longitudinal Residual Stress Profile
Thank You😊
Questions?