Manufacturing Development Strategies in Aviation Industry

Włodzimierz Adamski

Summary
Machine tool technologies, especially Computer Numerical Control (CNC), High Speed Machining (HSM) have emerged as effective mechanisms in the aerospace, automotive, and die and mould industries. These new technologies are attractive for competitive manufacturing because of their technical advantages, i.e. a significant reduction in lead-time, high product accuracy, and good surface finish. This paper describes the computational requirement and cutting parameters of HSM, look ahead programming and simulation.

Keywords: high speed machining, stability lobes diagrams, machining simulation

1. High speed machining

How the expression High Speed Machining (HSM) should be explained?
There are plenty of different definitions suggested, for example:

1. High cutting speed ($v_c$) machining,
2. High feedrate ($v_f$) machining,
3. High spindle speed machining,
4. High speed and feedrate machining,
5. High performance machining.

HSM usually refers to process of machining with high speed and high feed rates. For example, milling so-called „pocket” in aluminium frame of aircraft.

Address: Włodzimierz ADAMSKI PhD Eng., Polskie Zakłady Lotnicze – A Sikorsky Company, 3 Wojska Polskiego st., 39-300 Mielec, e-mail: w_adamski@pzmielec.com.pl
with very high values of volumetric material removal rate. Different definitions of HSM are based on Salomon research results "Process for the machining of metals (…)" [1], which were patented in 1931. For machine-part-tool system, HSM occurs when the increasing machining speed reduces machining forces ($F$) (Fig. 1).

![Fig. 1. Machining forces in relation to machining speed [8]](image)

HSM: $$\frac{\partial F}{\partial v_c} < 0$$  \hspace{1cm} (1)

CONVENTIONAL: $$\frac{\partial F}{\partial v_c} > 0$$  \hspace{1cm} (2)

Dynamical stability is very important when using HSM methods. Mativenga and Hon [2] have found the relation between vibrations arising from cutting forces and velocity changes. Five components have been indicated as significant for HSM:

1. Frequency of spindle

$$f_s = \frac{N}{60}, \text{ Hz}$$  \hspace{1cm} (3)

2. Frequency of tooth passing

$$f_{tp} = z f_s, \text{ Hz}$$  \hspace{1cm} (4)
3. Frequency of beam resonant

\[ f_b = 3,1560 \sqrt{\frac{EI}{ml^4}}, \text{ Hz} \quad (5) \]

4. Frequency of longitude rod resonant

\[ f_r = \frac{\pi}{2l} \sqrt{\frac{E}{\rho}}, \text{ Hz} \quad (6) \]

5. Frequency of chip creation

\[ f_c = \frac{v_c n_s}{60}, \text{ Hz} \quad (7) \]

where: \( N \) – rotational speed, rpm; \( z \) – flute number, \( E \) – elasticity modulus, Pa; \( I \) – inertia moment, kgm\(^2\); \( m \) – mass per unit length, kg/m; \( l \) – beam length, m; \( \rho \) – density, kg/m\(^3\); \( v_c \) – chip velocity, m/min; \( n_s \) – number of serrations per unit chip length, 1meter.

2. Defining machining efficiency

What is very important and typical for HSM is the fact that depth of cut \( a_e \) and \( a_p \), together with average chip thickness \( h_m \) remain on significantly lower level than for conventional machining. However, volumetric material removal rate \( Q \) is much higher than for traditional machining. It is caused by much higher feed speed \( V_f \).

Formulas for feed speed and material removal rate are listed below:

\[ V_f = f_z n a_e, \text{ mm/min} \quad (8) \]

\[ Q = \frac{a_p a_e V_f}{1000}, \text{ cm}^3/\text{min} \quad (9) \]

Analysis of stability lobes (Fig. 2) [3] shows that stable machining zone can be found below the stability lobes.
Above the curve there is unstable region, where chatters occur. Chatter means phenomenon that causes the tool or machined part to jerk or jump when being fed. Stable system is chatter-free depending on spindle rotates and depth of cut combination, what is shown on the stability lobes diagram above. Four examples had been analyzed (Fig. 2) machined with mill of $\phi = 20$ mm, 5 flutes and machining width = 20 mm, feed per tooth = 0.15 mm. With following values: rotational speed of 2000 rpm and depth of cut of 18 mm the material removal rate $Q = 540$ cm$^3$ is obtained. For speed of 21 000 rpm with 50 mm depth of cut system still remains in stable zone. The received material removal rate is 15 750 cm$^3$, so it is over 30 times larger (faster production). The formula for the depth of limiting cut layer (undeformed chip) – below the stability lobes – is as follows:

$$a_{pgp} = \frac{2 \cdot k \cdot \zeta}{K_c \cdot a_e \cdot z}$$ \hspace{1cm} (10)

where: $K_c$ - specific resistance of cutting force, $z$ - number of teeth, $k$ - stiffness coefficient, $\zeta$ - damping coefficient, $D$ - tool diameter, $a_e$ - axial approaching feed.
Stability results are shown in Table 1 [3]. This chart summarizes the test results for one combination of tool, tool holder and spindle. Running this test took about half an hour. The slanted region indicates stable cutting.

### Table 1. Stability results

<table>
<thead>
<tr>
<th>Rotational speed, rpm</th>
<th>6500</th>
<th>7000</th>
<th>7500</th>
<th>8000</th>
<th>8500</th>
<th>9000</th>
<th>9500</th>
<th>10000</th>
<th>10500</th>
<th>11000</th>
<th>11500</th>
<th>12000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate, mm/min</td>
<td>840</td>
<td>900</td>
<td>960</td>
<td>1 020</td>
<td>1 080</td>
<td>1 140</td>
<td>1 200</td>
<td>1 260</td>
<td>1 320</td>
<td>1 380</td>
<td>1 440</td>
<td>1 500</td>
</tr>
<tr>
<td>Chip load, mm/tooth</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td>0,075</td>
<td></td>
</tr>
<tr>
<td>Depth of cut, mm</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
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<td>4</td>
</tr>
</tbody>
</table>

In aviation industry HSM [4, 5] makes it possible to manufacture large complex thin-walled parts from integral blocks (Fig. 4). High cutting speed allows removing material with lower cutting forces, what does not result in part deformations during machining process. Main landing gear flap of C-17 air freighter had been produced as an assembly of parts manufactured from profiles and sheets. Using HSM technology the flap has been manufactured as single part on CNC machine with machining time of about 12 hours.

Machining a frame from single element reduced significantly its weight. Previous solution was an assembly of 20 parts. The frame integral version has allowed reducing 80% of the weight comparing to the assembly weight (Fig. 3).
3. Why Sikorsky Company uses high speed machining technology?

Table 2 shows the results.

Table 2. HSM benefit

<table>
<thead>
<tr>
<th>Machining parameters</th>
<th>Theoretical values</th>
<th>Assumed values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>1000 ft/min (305 m/min)</td>
<td>2500 ft/min (760 m/min)</td>
</tr>
<tr>
<td>Spindle rotations</td>
<td>7640 rpm</td>
<td>18 500 rpm</td>
</tr>
<tr>
<td>Feed per tooth</td>
<td>0.001&quot; (0.0025 mm)</td>
<td>0.005&quot; (0.13 mm)</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.25 (6.5 mm)</td>
<td>0.15&quot; (4 mm)</td>
</tr>
<tr>
<td>Material removal rate</td>
<td>1.9 cubic inches/min (31 cm³/min)</td>
<td>6 cubic inches/min (98 cm³/min)</td>
</tr>
<tr>
<td>Machining time</td>
<td>90 h</td>
<td>30 h</td>
</tr>
</tbody>
</table>

HSM spindles are high loaded what results mainly from high rotational speed and working in unstable chatter areas. It has a negative influence on construction elements of CNC (Computer Numerical Control) machine and lowers quality parameters of machined surfaces. Monitoring the spindle state
from the date of its purchase allows defining CNC machine’s characteristics of performance and analysing its changes in time. Regular measurements (for example once a three months) define spindle state and changes of its dynamical stiffness when operating. Renishaw QC10 ballbar diagnostic system in PZL Mielec allows conducting an automatic test for checking CNC machine’s geometry and faults of guide movements. Measuring results are presented as diagrams. Systematic measurements result in specifying needs of machine overhauls and planning them in the most convenient time. Monitoring technical state of CNC machines helps to find quickly the components needing service or repair.

High dynamic stiffness of CNC machine does not ensure stable work (without chatters) with any machining parameter.

Purchasing high quality CNC machine will not ensure high machining accuracy until adjusting optimal machining parameters.

![Fig. 4. The example of machining with Φ 12mm cutter. Semi-finished product dimensions = 120 mm x 752 mm x 2400 mm](image)

Cutting tool producers suggest using several tools with different length and diameter to deep pockets or small radius machining. This methodology allows the users to adjust tools and holders to specific production tasks and speed the machining up even a few times.

Other benefits of HSM machining are:
- simplified fixing (lower cutting forces),
- more clean mill edges => lower deformations during machining process,
- smoother surfaces => shorter finishing machining,
- lower consumption of cutting tools.
## 4. Examples of using HSM in PZL Mielec

The measuring results were applied to part presented on Fig. 5. Machining time of one operation in this case has been reduced from 32h to 8h, i.e. over 4 times.

![Fig. 5. Stage-of-the-art passenger plane part](image)

## 5. Look-ahead function

Introducing CNC machines into the industry has rapidly changed it. Problems with manufacturing of very complex surfaces no longer exist. Look-ahead function, used in CNC machines, allows foreseeing the event before it happens (for example mill damage) and preventing it effectively. There are also various systems for aiding CNC machining as for example OMATIVE Adapting System and monitoring spindle load during milling process. Monitoring spindle load during CNC machining process with OMATIVE System reduces machining time significantly. The following examples show reduction of labour consumption in numbers: 29.7% for aluminium alloy stringer machined in Boeing or 24.4% for stainless steel parts machined in Aerospatiale-EADS, Toulouse, France.

HSM technology together with CNC system needs integration with computer-aided manufacturing (CAM) and designing (CAD) in order to obtain faster, more effective production according to required quality level. Most CAM systems work in 3D environment together with CAD applications. CAD/CAM systems with proper quality eliminate the need of re-modeling the CAD model.
of machined part for CAM system. At the market there are many CAM systems able to „read” numerical models from CAD systems. Unigraphics, Surfcam, AutoCAD, CATIA or ProEngineer are the examples of such systems popular in industry.

CAM systems not only generate tool path, but are also used to verify and optimise the path to reduce the number of errors even to zero. VERICUT system is example of very good system which is independent from CAD/CAM systems. PZL Mielec uses VERICUT for part machining simulation and optimizing programs for CNC numerically controlled machines. By simulating machining programs on computer instead of hazardous testing on real CNC machine PZL Mielec has gained significant savings and profits. Shorter lead times have been obtained, CNC machines productivity has increased and machining quality level has improved (reduced number of rejects). The risk of program errors during CNC machining has been also reduced, because errors are detected on computer long before real machining process. Especially important issues are: function of preventing machining program errors and avoiding tool collision in working area, what results in reduced number of production rejects, avoiding damage of expensive CNC machine and time loss. It is obvious that client does not want to
be charged for the above. PZL Mielec has virtual models of all its modern CNC machines with tool holders, tools, vice, jaws and jigs. Virtual testing of machining programs is already a common practice. One more advantage of VERICUT system is “cheaper” education of CNC machine operators with the use of virtual CNC machines instead of real ones. Manufacturing parts on real CNC machines is significantly easier for operators after computer simulation of the machining. Figure 6 presents example of part machining simulation with 5-axis machines. Machining program analysis repeated by programmer (after postprocessor) allowed to prevent the collision on real CNC machine. How does the electronic information flow looks like at given manufacturer in practice? How is numerical model of a part transformed during production process into real part. Part model is designed in CATIA system.

Figure 7 [3] shows in practice the information flow during a part manufacturing. Numerical model of the part has been created in CATIA system. Next the model has been transmitted to SURFCAM system using direct CATIA-SURFCAM translator.

![Information flow and using CAD/CAM models in PZL Mielec in practice](image)

Part machining program has been also generated in SURFCAM and then “uploaded” by fibre optic media to CNC machine. Fixing tool has been manufactured basing on the numerical model designed in CATIA and mounted at CNC machine. Cutting tools have been mounted in tool holder using thermic
shrinking jig. Cutting tools have been measured in computer tool setup before transporting them to CNC machine in special cart. Part numerical model has been sent to Power Inspect measuring system by the use of IGES data exchange standard package. Next the real manufactured part has been inspected by measuring machine (CMM) and measuring results compared to numerical model of the part, generated in CATIA and sent to Power Inspect system. Data, jigs and cutting tools flows on Figure 7 are indicated by arrows.

6. Additional methods of improving machining productivity

If possible it is suggested to machine two (Fig. 8) or more parts from one billet (symmetrical/mirror image). Using the same setup time, billet is provided from store-room directly to work stand. Benefits from such solution are: material savings, reducing billet preparing time even to zero and the part is more stable during machining process. Figure 8 shows the example of material savings of 18%.

![Fig. 8. The way of parts holding in a frame type device](image)

Next examples are parts machined with the same fixing in vice with higher vice jaws (Fig. 9).
High Speed Machining advantages:
• cutting force reduction,
• small heat flow to workpiece, heat transferred into chips,
• reducing cycle time,
• increasing the quality of manufactured parts,
• reducing finishing machining,
• operation of cutting in stable zone (avoiding chatters),
• possibility of fine elements manufacturing.

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References


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