ROUGH TURNING OF INCONEL 718

Krzysztof Jemielniak

Summary

Paper presents comparison of cutting performance of several cemented carbide, CBN and whiskers tools in rough turning of Inconel 718. Objectives of the project were to identify the best tools from offered by four leading producers. Optimal machining conditions and the tools performances were established for rough turning of rigid and flexible workpieces. In the first case decisive criterion was tool life and productivity. In the second one, more important were the cutting forces in two aspects: stability (possible chatter) and flexibility of the part (possible deformations). Results showed that despite of all manufacturers claims of their tools superior performance, the tool selection should be carried out carefully, also taking into account optimization criteria.

Keywords: Inconel 718, rough turning, cutting ability

1. Introduction

Since many years, the machining of hardly machinable has caused serious problems in aviation and other manufacturing industries. Nickel-based superalloys are widely used in aircraft industry as they are exceptionally thermal resistant retaining mechanical properties up to temperature of 700°C [1]. However, they are very difficult-to-cut materials due to their high shear strength, work-hardening tendency, highly abrasive carbide particles in the microstructure, strong tendency to weld and form a built-up edge, and low...
thermal conductivity [2, 3]. Nickel-based superalloys are normally machined with WC-Co grades with cutting speeds in the order of 50 m/min. With the introduction of sialon materials, it is possible to increase the cutting speed by a factor of 5, and more recently silicon carbide whisker-reinforced alumina tools have made it possible to machine at cutting speeds of up to 10 times those used with cemented carbide [4].

Ceramic tools are suitable with regard to their high hardness, wear resistance, and chemical inertness even at high cutting speeds. However, their fracture toughness is much lower than that of the other widely used tool materials such as high speed steel and carbides.

The paper presents results of the project „Nickel Alloy Machining Optimization” being part of broader European project VITAL. The project was performed in the Warsaw University of Technology as subcontractor for WSK PZL Rzeszów. The results described in this paper aimed at selection of the best tools for rough turning of Inconel 718, allowing significant rise of cutting speeds. Another part of this project, dealing with finish turning, was presented in [5].

Two kind of machined elements had to be taken into account: rigid elements like disk and flexible elements like turbine case. Demands and cutting ability criteria in both cases were not the same. In the first case decisive criterion is tool life and productivity. In the second one, even more important are the cutting forces in two aspects: stability (possible chatter) and flexibility of the part (possible deformations).

Table 1. Tools selected for turning of flexible parts. All PVD TiAlN coated cemented carbide

<table>
<thead>
<tr>
<th>Tool</th>
<th>Tool holder &amp; insert</th>
<th>Cutting parameters</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCLCR1616H-09</td>
<td>$v_c = 50-70$ m/min $a_p = 0.5-2.5$ mm $f = 0.06-0.25$ mm/rev</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CCMT 120404-SM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SCLCR2020K09</td>
<td>$v_c = 25-120$ m/min $a_p = 0.08-0.8$ mm $f = 0.04-0.16$ mm/rev</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CCGT09F302HP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SCLCL 2020K12</td>
<td>$v_c = 60-80$ m/min $a_p = 0.5-2.0$ mm $f = 0.10-0.21$ mm/rev</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CCMT120404-MM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>PWLNR2020K6</td>
<td>$v_c = 55$ m/min $a_p = 0.2-1.5$ mm $f = 0.1-0.25$ mm/rev</td>
<td></td>
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<tr>
<td></td>
<td>WNNMG060404-MF1</td>
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</table>
Four leading tools producers were invited to the project and recommended their best solutions of the problem. The producers suggested several tools for the task, and after preliminary analysis the potentially best out of each producer proposal were selected. The producers also suggested initial cutting parameters for their tools. The selected tools and cutting parameters suggested by producers were presented in Table 1 and 2.

<table>
<thead>
<tr>
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<th>Tool holder &amp; insert</th>
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</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>MCLNR2525M-12 CNMA120408T CBN</td>
<td>( v_c = 50-200 \text{ m/min} ) ( a_p = 0.1-3 \text{ mm} ) ( f = 0.05-0.25 \text{ mm/rev} )</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>411157-3VRS RCGX090700E SiAlON</td>
<td>( v_c = 140-290 \text{ m/min} ) ( a_p = 0.2-2.0 \text{ mm} ) ( f = 0.063-0.25 \text{ mm/rev} )</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CRSNR2525M12 RNGN120700T1020 SiAlON</td>
<td>( v_c = 250-300 \text{ m/min} ) ( a_p = 2-2.5 \text{ mm} ) ( f = 0.15-0.20 \text{ mm/rev} )</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>CRDCL 3225P09-A RCGX090700E whisker</td>
<td>( v_c = 250-300 \text{ m/min} ) ( a_p = 2-2.5 \text{ mm} ) ( f = 0.15-0.20 \text{ mm/rev} )</td>
<td></td>
</tr>
</tbody>
</table>

2. Cutting force testing in turning

In case of turning of flexible parts (Table 1) all producers had offered PVD TiAlN coated cemented carbide tools. For those tools cutting speed \( v_c = 50 \text{ m/min} \) was applied. In case of turning of rigid parts (Table 2) producers had offered ceramic (SiAlON or whisker) or CBN tools, which can cut with much higher cutting speed, thus here \( v_c = 200 \text{ m/min} \) was applied. General purpose emulsion was used as coolant in all tests. To make cutting force measurements comparable, compromise chip cross section was selected: depth of cut \( a_p = 2 \text{ mm} \), feed \( f = 0.2 \text{ mm/rev} \).

Workpieces were Inconel 718 bars of diameter 100 mm. The cutting force sensor Kistler 9263 with charge amplifiers 5001 was used for cutting force measurements. In each test cutting force signals were registered during 15 seconds with sampling frequency \( f_s = 10 \text{ kHz} \). In such signals central, stable parts were selected for average cutting force values calculation.
Figure 1 presents average cutting force values obtained during rough turning. Generally the lower force values the better. Main cutting force $F_c$ decides on cutting power, thus on heat generation, which is important for surface integrity. Distribution of the cutting forces in plane $P_r$ (relation between $F_f$ and $F_p$) is strongly dependant on tool geometry and is very important for stability, workpiece deflections and surface integrity. Especially important is the passive force $F_p$ directed against the machined surface, usually in a direction of smaller workpiece stiffness, so the smaller it is the better.

Tools dedicated for flexible parts (carbides) were applied with cutting speed $v_c = 50$ m/min. All tools had approach angle $\kappa_r = 95^\circ$, which resulted in advantageous relatively small passive forces $F_p$. The smallest forces values obtained using tool 2 including close to zero passive force. This excellent result was achieved due to very small nose radius $r_\varepsilon = 0.2$ mm. The second best result as far as $F_p$ is concerned was achieved by tool 1, however main cutting force $F_c$ and the feed force $F_f$ here were relatively high. Therefore the tool 3 with higher $F_p$ but lower $F_c$ and $F_f$ can be considered as equally good. The worst result was obtained by the tool 4.

Tools dedicated for rigid parts (SiAlON or whisker ceramics and CBN) were used with cutting speed $v_c = 200$ m/min. Here definitely best results was achieved by tool Iscar IB90, as it has advantageous for cutting forces geometry. Three round inserts naturally caused very high passive forces which can be acceptable for roughing rigid parts only.
3. Tool life testing

Tool life test were performed up to 7 min of cutting time or to tool wear threatening with catastrophic tool failure (CTF) while roughing or eminent worsening of surface finish while finishing. Rough turning of flexible parts was performed with depth of cut \( a_p = 1 \) mm and feed \( f = 0.1 \) mm/rev while rigid parts were machined with depth of cut \( a_p = 2 \) mm and feed \( f = 0.2 \) mm/rev. Length of single pass corresponded with 20-40 mm on 100 mm diameter workpiece. In order to avoid negative influence of entering of tool into material, workpiece edge was phased with angle 45°, and tool was always withdrawn under 45°. Tool wear was measured using toolmakers microscope.

3.1. Flexible parts

Tool wear – cutting time curves obtained for rough machining of flexible parts are presented in Fig. 2.

![Fig. 2. Tool life test results for rough machining of flexible parts with \( a_p = 1 \) mm and \( f = 0.1 \) mm/rev: a) tool 1, b) tool 2, c) tool 3, d) tool 4](image)

Tool 1 was used with \( v_c = 70, 90 \) and 110 m/min. For smaller cutting speeds tool wear was uniform width of the flank, but for \( v_c = 110 \) m/min there were distinguished maxims at the both ends of tool-workpiece contact zone.
For tool 2 (tested with the same cutting speeds) dominant form of tool wear was flank wear at the corner, which was caused by very small nose radius \( r_e = 0.2 \), advantageous for small cutting forces, but costly from tool life point of view.

Tool 3 was tested with \( v_c = 70 \) and 90 m/min. In both tests high flank wear was achieved without CTF which is advantageous.

Three tests were carried out using tool 4 – with \( v_c = 70, 90 \) and 120 m/min. In all tests tool wear was uniform width of the flank, however tests with \( v_c = 90 \) and 120 m/min ended with catastrophic tool failure (CTF).

In Figure 3 tool life test for all tools for rough machining of flexible parts are gathered together for comparison. Cutting speed \( v_c = 110 \) m/min appeared much too high for all tools, therefore only \( v_c = 70 \) and 90 m/min are presented here. Tool 1 was superior in both cutting speeds and was the only one which reached assumed tool life \( T = 7 \) min for \( v_c = 90 \) m/min.

For \( v_c = 70 \) m/min tools 3 and 4 performed almost the same good results, while for \( v_c = 90 \) m/min the latter was little better than the former, but the difference does not seem to be evident, thus these two tools can be considered as equivalent as far as tool life is concerned. Apparently worse results were achieved by tool 2. It should be applied only if very low workpiece stiffness necessitates reduction of the cutting forces even at the cost of tool life.

![Fig. 3. Results of tool life test for rough turning of flexible parts: a) \( v_c = 70 \) and b) 90 m/min](image)

### 3.2. Rigid parts

Wear of tool 5 was very fast. Characteristic was notch wear just out of tool – workpiece contact zone. State of the insert after \( t = 0.44 \) min of cutting with \( a_p = 2 \) mm, \( f = 0.2 \) mm/rev and \( v_c = 150 \) m/min (Fig. 4). Therefore the tool was withdrawn from further experiments.

While machining with tool 6 the chatter vibration occurred, however they were not very strong, nevertheless cutting was possible. Tool wear proceeded
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gradually up to some VB = 0.3 mm, then chipping of the cutting edge appeared, leading finally to the catastrophic tool failure.

![Tool Insert](image)

**Fig. 4.** Insert of tool 5 after t = 0.44 min of cutting with
\( a_p = 2 \text{ mm, } f = 0.2 \text{ mm/rev and } v_c = 150 \text{ m/min} \)

Tool life test results for this and the 8th tool, used with \( a_p = 2 \text{ mm and } f = 0.2 \text{ mm/rev} \) are presented in Fig. 5.

![Tool Life Test Results](image)

**Fig. 5.** Tool life test results for rough machining of rigid parts with
\( a_p = 2 \text{ mm and } f = 0.2 \text{ mm/rev} \): a) tool 6, b) tool 8

While using tool 7 strong chatter appeared for \( a_p = 0.5 \text{ and } 2 \text{ mm, } f = 0.01 \text{ to } 0.2 \text{ mm/rev, and } v_c = 50 \text{ to } 150 \text{ m/min} \). Resultant surface is presented in Fig. 6. The vibrations were so severe that for \( a_p = 2 \text{ mm } f = 0.2 \text{ mm/rev, } v_c = 100 \text{ m/min} \), catastrophic tool failure occurred already after t = 0.3 min (see Fig. 6). Therefore the tool was withdrawn from experiment.
Two tests with $v_c = 250$ m/min and 300 m/min were performed using tool 8. Tests were finished when state of the cutting edge worsened and there was a danger of catastrophic tool failure. Until then cutting was excellent, without any problems, and quite good surface finish. In the first case tool life was 4.8 min which is quite acceptable. Cutting speed $v_c = 300$ m/min recommended by producer appeared too high – tool life $T = 3$ min. Results of these tests were presented in Fig. 5.

Thus out of four tested tools only two worked satisfactory tool 6 and 8. The latter however achieved much higher tool life and productivity – for $v_c = 250$ m/min $T = 4.8$ min, volume of machined material was 480 cm$^3$. The second tool under this cutting speed could cut only for 2 min, which is rather not good enough. Satisfactory tool life $T = 5$ min was achieved only with $v_c = 150$ m/min, however this means 300 cm$^3$ of removed material.

Tool 5 was just not wear resistant enough to be used in these cutting conditions.

Tool 7 caused strong chatter, which can be attributed to the machine tool not stable enough. It cannot be excluded that this tool could perform much better on more stable machine tool. Nevertheless such demand limits application range of the tool.

4. Inconel 718 rough Turning optimization - summary

Results of all experiments were summarized in tables 3 and 4, altogether with tool evaluation based on above criteria.

4.1. Flexible parts

In machining of flexible parts the cutting force values play important role. The best tool from this point of view – tool 2 – appeared very little wear resistant, so it may be recommended only in particular cases, when the small
cutting forces are indispensable for machining very flexible parts. Tool 1 achieved the best score concerning tool life. Even though cutting force $F_c$ and feed force $F_f$ are relatively high (see Figure 1), the passive force $F_p$ deciding on the workpiece deflections is relatively low – only tool 2 had smaller passive force. Therefore the tool can be considered as the best for rough turning of flexible parts.

Table 3. Rough turning of flexible parts

<table>
<thead>
<tr>
<th>Tool material</th>
<th>Tool</th>
<th>Cutting forces</th>
<th>T - $v_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>++</td>
<td>+++</td>
<td>best</td>
</tr>
<tr>
<td>2</td>
<td>+++</td>
<td>–</td>
<td>second</td>
</tr>
<tr>
<td>3</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

+++ the best ++ good + acceptable – not acceptable

The second choice can be tool 3, which achieved quite good tool life and relatively low cutting forces.

So finally:

Rough turning of flexible parts:

1: Tool 1: SCLCR1616H-09, with insert CCMT 120404-SM
   $a_p=1$mm, $f=0.1$mm/rev, $v_c=90$m/min, productivity $Q=9$cm$^3$/min, $T=7$ min,
   material removed during one tool life $V=45$ cm$^3$

2: Tool 2: SCLCL 2020K12, with insert CCMT120404-MM
   $a_p=1$mm, $f=0.1$mm/rev, $v_c=90$m/min productivity $Q=9$cm$^3$/min, $T=5$ min,
   material removed during one tool life $V=45$ cm$^3$
4.2. Rigid parts

Evidently the best tool for rough turning of rigid parts appeared to be tool 8, which can be used with the cutting speed $v_c = 250 \text{ m/min}$ still giving tool life higher than 4 min. The tool life for the next best tool 6 under the same cutting conditions was twice smaller.

Tool 6, which cut with the smallest cutting forces appeared to be very good as far as wear resistance is concerned. As the cutting forces are not that important in rough machining, this tool must be considered as unacceptable.

Tool 7 caused strong chatter making machining impossible. However it cannot be ruled out, that on much more dynamically stable machine this tool can be used successfully.

<table>
<thead>
<tr>
<th>Tool material</th>
<th>Tool</th>
<th>Cutting forces</th>
<th>$T - v_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBN</td>
<td>5</td>
<td>+++</td>
<td>–</td>
</tr>
<tr>
<td>SiAlON</td>
<td>6</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>SiAlON</td>
<td>7</td>
<td>++</td>
<td>? chatter</td>
</tr>
<tr>
<td>Whisker</td>
<td>8</td>
<td>++</td>
<td>+++</td>
</tr>
</tbody>
</table>

+++ the best ++ good + acceptable – not acceptable

So finally:

**Rough turning of rigid parts:**

1. Tool 8 CRDCL 3225P09-A with insert RCGX090700E, whisker, $a_p = 2\text{ mm}$, $f = 0.2\text{ mm/rev}$, $v_c = 250\text{ m/min}$, productivity $Q = 100\text{ cm}^3/\text{min}$, $T = 4\text{ min}$, material removed during one tool life $V = 400\text{ cm}^3$

2. Tool 6 411157-3VRS, with insert RCGX090700E, SiAlON, $a_p = 2\text{ mm}$, $f = 0.2\text{ mm/rev}$, $v_c = 150\text{ m/min}$, productivity $Q = 60\text{ cm}^3/\text{min}$, $T = 5\text{ min}$, material removed during one tool life $V = 300\text{ cm}^3$
It should be underscored, that cutting parameters presented above, selected for particular tools should be treated as preliminary choice, which has to verified in shop floor conditions. Results showed that despite of all manufacturers claims of their tools superior performance, the tool selection should be carried out carefully, taking both optimization criteria into account.

References


Received in May 2009