INFLUENCE OF TOOL BALANCING ON MACHINED SURFACE QUALITY IN HIGH SPEED MACHINING

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Abstract: High speed machining has some differences according to conventional milling. The main difference is higher rotational speed of the spindle (40 000 min⁻¹ and higher). During high speed spindle rotations more dynamic forces are rising, which are affecting bearings, frame and the whole machine. The forces are efforting vibrations furthermore causes worse quality of machined surface and may damage the spindle. Minimization of these forces is essential. According to that, the tool balancing machines are used. Tool balancing should provide better mass set out around the tool axis. Two identical tools were balanced according to ISO 1940-1 standard at two different levels. Aluminum plate was used as an experimental part. Both milled surfaces were scanned with 3D microscope and surface roughness was evaluated. Results showed High speed machining with balanced tool provided better surface quality than conventional milling as well as worse balanced tool.

Key words: Tool balancing, unbalance, high-speed machining, 3D microscope, surface quality

1. INTRODUCTION

The key-stone in high-speed milling is to reach higher surface quality and removal rate with high cutting speed and in the same way reach lower tool wear and lower cutting forces. Large amount of heat generated at the cutting edge is minimally transferred to a material and tool at high-speed milling. In order to reach high surface quality, adequate chip removing rate is an important parameter [1]. By high-speed milling it is possible to achieve surface roughness at level Ra 0,2 µm [2]. Important parameter affecting achieved surface roughness is run out, caused by unbalance of the tool, tool holder and the spindle. Importance of run out is rising with frequency of spindle rotation, furthermore with rising of centrifugal forces affecting tool in high-speed milling. To verify theoretical knowledge, an experiment was realized.

2. OUT - OF - BALANCE

Unbalance of a rotational part comes from its geometric shape depending on its functionality. Unbalance of parts symmetrical by axe like tools and tool holders are, is caused by inaccuracy of shape and size, non-homogeneity of material, nonsymmetrical parts e.g. clamping screw in some types of tool holders, clamping slot on some tool shanks and run out of a tool holder. Unbalanced tool arrangement can be explained as a rotational part, where momentum central axis is not identical with axis of rotation (Fig.1) [3]. Balancing is a process of mass correction around the central momentum axis by loading or unloading of mass. The aim is to reach identical position of momentum and rotational axis of the tool arrangement as well as it is possible. That preserves dynamic forces

\[ G = \text{level of balancing} \ (G1,0; \ G2,5; \ G6,3) \ [\text{ms}^{-1}], \]

\[ m = \text{Tool arrangement weight [kg]}, \]

and vibrations in bearings in allowed limits when required rotations are reached [4].

Fig.1. Central momentum axis and rotational axis [5]

2.1 Calculation of unbalance

In High Speed Cutting, the maximum unbalance is characterized in ISO 1940-1 standard. This standard presents levels of G for certain rotational frequencies and rotational parts. For rotational tool arrangements, G
level should be at least 2.5 $\text{ms}^{-1}$ at maximum spindle rotational speed. According to unbalance G level, rotational speed and tool arrangement weight, maximum allowed unbalance can be calculated as [6]:

$$U_{zv} = \frac{G \cdot 9.549 \cdot m}{n} \quad \text{[gmm]} \quad (1)$$

Where: $U_{zv}$ is remaining unbalance [gmm],
$n$ – Rotational speed [min$^{-1}$],
9549 – Constant [-].

2.2 Ways of tool arrangement balancing

Ways of tool arrangement balancing can be divided as following:
1. Balancing in one balancing level: static and rotational unbalance.
2. Balancing in two balancing levels: momentum and dynamic unbalance.

Balancing in one balancing level is used when gravity center is out of rotational axis (Fig.2). The aim is to move the gravity center of tool arrangement into rotational axis. When rotational balancing is employed, centrifugal force perpendicular to axis is rising. Rotational unbalance is eliminated in one level; balancing level position is irrelevant in this case. In practice, balancing in one level is enough. It can be said, this is valid for rotational parts, where the ratio of length to diameter is smaller than 0.2 [4].

After balancing in one level, momentum unbalance may remain. In momentum unbalance center of gravity is identic with rotational axis and two unbalances are rotated 180° degrees to each other (Fig.3). This caused vibrations characterized by swinging movement. In order to eliminate the unbalance it is necessary to use momentum with contradictory direction and balancing in two levels.

Dynamic unbalance is caused by two unbalances with different angle position. Dynamic unbalance can be divided into static and moment unbalance.

3. EXPERIMENTAL

Experimental part is a plate made of aluminum according to standard EN6061 with dimensions 80 x 80 10 mm divided into 3 areas, as is figured out in Fig. 4. For experiments DMG Sauer Ultrasonic 20 linear machine tool was used and Seco JV 40 HEMI carbide monolith cutting tools with diameter 8mm. Both tools were clamped into shrink fit holders and the arrangement were balanced by Haimer Tool Dynamic 2009 with G levels according to Table 1.

Fig. 4. Experimental part

3.1 Cutting conditions

Stability of cutting process was one of the most important conditions in cutting conditions setup. Feed $f_z$ was considered as a constant and rotations were selected based upon balance level G and cutting parameters were obtained through analytical calculation (for cutting speed and feed). Selected values for feed velocity and rotations are in Table 2. According to selected cutting parameters and tool diameter, standard ISO 1940-1 were selected for tool balancing. At nowadays machine tools and tool shanks producers start using standard DIN 69888 especially for small diameters and weights of tools, where ISO 1940 -1 standard is not adequate.

Fig. 5. Cutting process on DMG Ultrasonic 20 linear machine tool with balanced tool arrangement by eccentric balancing rings on shrink fit tool holder with HSK 32 adaptor for high-speed milling.
3.2 Experiment realization

Surface of experimental part were divided into three areas, where each of them were machined under different cutting conditions (different rotations and feed velocity) according to a Table 1 with a tool arrangement balanced to a G level of 1.6. The other side of a part was machined under different cutting conditions with tool arrangement balanced to a G level of 6.3. Surface quality of machined surface was analyzed by confocal microscope LSM 700 with ZEISS optics. Results are shown in Table 3; the cutting process is in Fig.5; the output from 3D microscope is shown in Fig. 6.

<table>
<thead>
<tr>
<th>Rotation s (min⁻¹)</th>
<th>Feed vf (mm. min⁻¹)</th>
<th>Rotations (min⁻¹)</th>
<th>Feed vf (mm.min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 000</td>
<td>2016</td>
<td>6 000</td>
<td>672</td>
</tr>
<tr>
<td>24 000</td>
<td>2688</td>
<td>12 000</td>
<td>1344</td>
</tr>
<tr>
<td>30 000</td>
<td>3360</td>
<td>18 000</td>
<td>2016</td>
</tr>
</tbody>
</table>

Cutting depth ap = 0.5 mm

Table 1. Cutting conditions

Fig.6. 3D profile map of milled surface with rotations of 18 000 min⁻¹

<table>
<thead>
<tr>
<th>Surface area</th>
<th>Ra [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1. (18 000 min⁻1)</td>
<td>1,031</td>
</tr>
<tr>
<td>Area 2. (24 000 min⁻1)</td>
<td>0,945</td>
</tr>
<tr>
<td>Area 3. (30 000 min⁻1)</td>
<td>0,76</td>
</tr>
<tr>
<td>Area 4. (6 000 min⁻1)</td>
<td>0,882</td>
</tr>
<tr>
<td>Area 5. (12 000 min⁻1)</td>
<td>1,03</td>
</tr>
<tr>
<td>Area 6. (18 000 min⁻1)</td>
<td>0,979</td>
</tr>
</tbody>
</table>

Table 2. Measured Ra values

4. CONCLUSION

Based upon measured values, shown in Table 2 following charts (Chart 1, Chart 2.) were created for better imagination according to equations written below. For both charts creation, method of ordinary least squares was used. The calculation for experiment with tool arrangement balanced to a G level of 6.3 is as following.

\[
\begin{align*}
(\Sigma x_i)^2 &= 12,112 = 146,7; \quad x_i = \log z_i; \quad y_i = \log w_i \\
\end{align*}
\]

Regression coefficients:

\[
\begin{align*}
b_0 &= \frac{\Sigma y_i \Sigma x_i^2 - \Sigma x_i \Sigma x_i y_i}{n \Sigma x_i^2 - (\Sigma x_i)^2} = -0.43 \\
b_1 &= \frac{n \Sigma x_i y_i - \Sigma x_i \Sigma y_i}{n \Sigma x_i^2 - (\Sigma x_i)^2} = 0.101 \\
\end{align*}
\]

Then Ra calculation is as following:

\[
\begin{align*}
w (Ra) &= c. \ z (n)^{0.101} \\
\end{align*}
\]

Chart 1 shows relation between surface roughness characterized by Ra and rotations where the G level of balanced tool was 6.3. The chart may be explained as following: surface roughness, represented by Ra was rising until the rotations reached approximately 13 000min⁻¹, since that we can see decreasing of roughness. This effect may be caused by the transformation of cutting conditions from conventional to high speed milling conditions. According to tool manufacturer’s recommendations, rotations for selected tool should reach a value of 19890min⁻¹.

The calculation for experiment with tool arrangement balanced to a G level of 1.6 is as following:

\[
\begin{align*}
Meas. N. & \quad [z_i \quad [\text{min-1}] \quad x_i \quad x_i^2 \quad w_i \quad [\mu m] \quad y_i \quad x_i, \ y_i^2 \\
1. & \quad 6.000 \quad 3.778 \quad 14,273 \quad 0,882 \quad -0,034 \quad -0,204 \\
2. & \quad 12.000 \quad 4.079 \quad 16,638 \quad 1,031 \quad 0,012 \quad 0,048 \\
3. & \quad 18.000 \quad 4.255 \quad 18,105 \quad 0,979 \quad 0,009 \quad 0,038 \\
\Sigma n = 3 & \quad 36.000 \quad 12,111 \quad 49,016 \quad \Sigma y_i = -0,051 \quad \Sigma x_i \cdot y_i = -0,194 \\
\end{align*}
\]
Table 4. Ordinary Least squares input values for G 1.6

<table>
<thead>
<tr>
<th>xi</th>
<th>xi2</th>
<th>wi</th>
<th>yi</th>
<th>xi, yi</th>
</tr>
</thead>
<tbody>
<tr>
<td>18000</td>
<td>4.255</td>
<td>18, 105</td>
<td>0.013</td>
<td>0.055</td>
</tr>
<tr>
<td>24000</td>
<td>4.380</td>
<td>19, 184</td>
<td>0.945</td>
<td>0.024</td>
</tr>
<tr>
<td>30000</td>
<td>4.477</td>
<td>20, 043</td>
<td>0.769</td>
<td>-0.119</td>
</tr>
</tbody>
</table>

Σn = 3
Σyi = 72, 000
Σxi = 13, 082
Σxi2 = 57, 332
Σyi = -0.13
Σxi . yi = -0.582

Table 4. Ordinary Least squares input values for G 1.6

\[(\Sigma x_i)^2 = 13, 082^2 = 171, 13; \ x_i = \log z_i; \ y_i = \log w_i\]

Regression coefficients:

\[b_0 = \frac{\Sigma y_i.\Sigma x_i^2 - \Sigma x_i . \Sigma x_i y_i}{n. \ \Sigma x_i^2 - (\Sigma x_i)^2} = -0.0357,332-13,082,(-0.582) = 0.18\]

\[b_1 = \frac{n. \Sigma x_i y_i - \Sigma x_i . \Sigma y_i}{n. \ \Sigma x_i^2 - (\Sigma x_i)^2} = 3.(-0.582)-13,082,(-0.13) = -0.05^5\]

\[b_0 = \log c \rightarrow c = 10^{b_0} \quad w = c, z^k \]

\[b_1 = 10^{0.18} \quad k = b_1^{-1} \quad c = 1, 51 \quad k = - 0.05\]

Then Ra calculation is as following:

\[w (Ra) = c. z (n)^{-0.05}\]

Chart 2. Surface roughness flow on a surface machined with tool balanced to a G level of 1.6

Chart 2 Shows surface roughness flow in High speed milling with tool balanced to a G level of 1.6. Explanation of chart is as following: decreasing of surface roughness is caused by cutting speed rising, where in high speed machining, cutting conditions are changing. In High speed machining various changes are raising especially heat transfer and chip removing, which caused surface roughness declination. Surface quality is one of the most important benefits of high-speed machining.

The influence of tool balancing in possible to evaluate according to a surface roughness characterized by Ra and its relation to rotations at level of 18 000. This rotation speed was used both for G level of 6.3 and G level of 1.6. From Charts 1 and 2 or Table 2 it is clear that better G level provided better surface quality, however the difference at this rotation speed level is not very high. We can assume that the difference of surface roughness will rise with rotation speed. According to a ISO 1940 -1 standard it is not possible to use tool arrangement with balance level G of 6.3 for higher rotational speed like it was used, it will produce high centrifugal and dynamic forces and may cause breakage of spindle bearings or the whole spindle. Due to we can only suppose that surface quality decreasing in relation with rotational speed raising is valid.

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5. REFERENCES


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