Abstract: There is a strong interest both in mining and quarrying industry for the development of mechanical components such as jaws and mills made of high wear resistance materials. Hadfield steel is particularly resistant to abrasion wear and it is suitable for such an application. In recent years, a new metallurgical procedure has enabled the production of Hadfield steel with dispersion of Ti(C,N), which further increases the wear resistance of the material but severely reduces its machinability. In this work, a comparison of commercial tool grades and geometries for machining special Hadfield steel is presented. Specifically, surface roughness, chip form and tool life obtained by applying the selected tools were investigated and discussed. Some suggestions for tool selection are finally presented.

Keywords: TURNING, MACHINABILITY, HADFIELD STEEL

1. Introduction

There is an increasing industrial interest for materials characterized by high wear resistance, thanks to their numerous applications. Metal Matrix Composites – MMC – are innovative materials characterized by a fine dispersion of reinforcing particles onto a metallic matrix. Such materials are difficult to machine using conventional cutting processes and the productivity is generally poor. For this reason, experimental studies are required for identifying adequate cutting tools and optimal cutting conditions.

The Hadfield steel is a non-magnetic austenitic steel, containing about 1.2% of carbon and 12.5% of manganese. It is used in different engineering applications such as rolling parts for steel-making factories and wear-resistant components of machining equipments. After appropriate thermal treatments (such as tempering process), the initially fragile cast steel can achieve excellent wear resistance and very high toughness. This feature is emphasized when thermal treatments promote the precipitation of carbides and nitrides such as Ti(C,N), which determine a general increase of material mechanical properties. However, due to the high hardness, low thermal conductivity and strain hardening behavior of the Hadfield steel, its machinability is very low.

There are few publications in this field. Marinov [1] investigated the influence of chemical composition and grain size of reinforcing particles on machinability when the material was machined by carbide tools. Hornig et al. [2] derived a mathematical relationship between tool performance (quality surface and tool life) and process parameters using ceramic tools. Özler et al. [3] reported a study of machinability with sintered cutting tool considering surface temperature and cutting parameters. Kopac [4] investigated the surface integrity after the cutting process by applying cemented carbide or CBN tools.

Some other relevant papers published in this field are: [5], [6], [7] [8], [9], [10], [11], [12] who mainly focused on the machinability of MMC with Al/SiC reinforcing particles, by applying different tools materials and geometries. In most of these research works, the machinability was characterized in terms of surface quality, cutting tools, tool life and tool wear mechanisms.

On the contrary, it is very difficult to find technical information regarding the machinability of Hadfield steel with Ti(C,N) reinforcing particles. Accordingly, the aim of this research work was to experimentally investigate the machinability of this material. For this purpose, different commercial tools were compared in terms of surface quality, cutting tool, tool life and tool wear mechanisms.

2. Experimental set-up and procedure

Turning tests were performed on a turning and milling machine centre OKUMA Multus B300 (Figure 1(a)) in dry cutting conditions. The workpiece material was cast Hadfield steel (C 1.20%-1.40%, Mn 11.50 -14.50%, Cr<2.00%; 550 Vickers Hardness) reinforced by particles of Ti(C,N). Workpiece size was 100 mm diameter and 150 mm length.

Tests were performed in dry conditions for environmental purposes, although the application of lubricant is recommended in productive conditions to increase tool life.

After each pass in turning, high resolution photos of the cutting edge were automatically acquired by using a portable digital microscope mounted on the machine tool, see Figure 1(b). Machined surface was observed by visual inspection in order to detect defects and surface roughness was measured by means of a portable contact surf-tester Mitutoyo mounted directly on the machine tool head (Figure 1(c)).

Commercial cutting tools suitable for machining steel or cast iron in finishing or semi-finishing conditions by two different suppliers (denoted by M1 and M2) were selected. All tools were rhombic (with 80° tool included angle) with nose radius rε of 0.4 mm; cemented carbide grades with different multilayer CVD coatings were tested. Negative basic-shape inserts of type CNMG120404 (M1N1, M1N2, M1N3, M2N1) were clamped on a Sumitomo PCLNL 2525M12-S toolshank; positive basic-shape inserts type CCMT120404 (M1P1, M1P2, M1P3, M2P1) were clamped on a Sandvik SCLCR 2525M12 toolshank. Working cutting edge angle χ was 95° for all the cutting tools. The characteristics of the cutting inserts and the effective normal rake angles obtained by combining insert geometry with toolshank orientation are listed in Table 1.
3. Preliminary tests

The aim of preliminary cutting tests was to compare the cutting tools in terms of surface roughness and chip control. For this purpose, a Design of experiments was carried out, see Table 2.

Tab 2. Preliminary DOE

<table>
<thead>
<tr>
<th>Factor</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (v_c) [m/min]</td>
<td>3</td>
<td>20, 30 and 40</td>
</tr>
<tr>
<td>Depth of cut (a_p) [mm]</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed (f) [mm/rev]</td>
<td>3</td>
<td>0.12, 0.16 and 0.20</td>
</tr>
<tr>
<td>Tools</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

In order to represent the behaviour of surface roughness \(R_a\), the following model was adopted

\[ R_a = C_0 + C_{vc} v_c + C_f f + C_{vcf} v_c f + C_{vcf^2} v_c^2 f^2 \]  

where feed \(f\) is expressed in mm/rev, cutting speed \(v_c\) is expressed in m/min, while \(C's\) are unknown model coefficients which were determined by performing linear regression on experimental data. Model coefficients, squared linear correlation coefficient \(R^2\) as well as qualitative evaluation of chip form for each commercial tool are reported in Table 3. Moreover, confidence interval of roughness values for a given combination of cutting parameters is shown in Figure 3.

From the analysis of the obtained results, best and most repeatable surface quality was achieved by applying M1N2 and M1P2 cutting tools.

Table 3. Test results from roughness observation \((a_p = 0.5\text{mm}, v_c = 40\text{ m/min}, f = 0.12\text{mm/rev})\)

<table>
<thead>
<tr>
<th>Code</th>
<th>(C_0)</th>
<th>(C_{vc})</th>
<th>(C_f)</th>
<th>(C_{vcf})</th>
<th>(C_{vcf^2})</th>
<th>(R^2)</th>
<th>Chip form</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1N1</td>
<td>-2.37</td>
<td>0.01</td>
<td>33.69</td>
<td>-49.48</td>
<td>-1.41</td>
<td>79.2</td>
<td>short</td>
</tr>
<tr>
<td>M1N2</td>
<td>-4.62</td>
<td>0.09</td>
<td>68.29</td>
<td>-187.5</td>
<td>-0.95</td>
<td>89.0</td>
<td>short</td>
</tr>
<tr>
<td>M1N3</td>
<td>0.47</td>
<td>-0.01</td>
<td>-0.35</td>
<td>44.27</td>
<td>0.22</td>
<td>90.6</td>
<td>short/medium</td>
</tr>
<tr>
<td>M2N4</td>
<td>-2.85</td>
<td>0.05</td>
<td>42.75</td>
<td>-89.58</td>
<td>-0.46</td>
<td>87.0</td>
<td>short</td>
</tr>
<tr>
<td>M1P1</td>
<td>-4.86</td>
<td>0.11</td>
<td>73.06</td>
<td>-177.60</td>
<td>-1.19</td>
<td>89.0</td>
<td>short</td>
</tr>
<tr>
<td>M1P2</td>
<td>-2.51</td>
<td>0.01</td>
<td>38.73</td>
<td>-81.77</td>
<td>-0.01</td>
<td>91.2</td>
<td>short</td>
</tr>
<tr>
<td>M1P3</td>
<td>-4.83</td>
<td>0.14</td>
<td>68.85</td>
<td>-171.35</td>
<td>-1.39</td>
<td>89.5</td>
<td>medium</td>
</tr>
<tr>
<td>M2P4</td>
<td>-0.67</td>
<td>-0.04</td>
<td>16.40</td>
<td>-2.60</td>
<td>0.62</td>
<td>90.0</td>
<td>short</td>
</tr>
</tbody>
</table>

4. Tool wear tests

Tool wear tests were done with cutting parameters given in Table 4. The flank wear-land width \(V_B\) was chosen to characterize tool wear. The threshold \(V_{B,max}=0.2\text{ mm}\) was considered as tool wear criterion.

Figure 2. Surface roughness for different tools \((95\%\text{ confidence intervals; } a_p=0.5\text{mm}, v_c=40\text{ m/min}, f=0.12\text{mm/rev})\)

Figure 3. Effects of tool wear on negative basic-shape cutting inserts type CNMG120404.

Similarly, primary flank face, rake face and secondary flank face of each positive basic-shape tool (type CCMT120404) are shown in Figure 6, while the progression of tool wear \(V_B\) and the behavior of surface roughness \(R_a\) are reported in Figures 7 and 8, respectively.
Among CNMG120404 type cutting inserts, best results in terms of tool life were achieved by applying M1N1 and M2N4 cutting tools (average tool life $T=6.5$ min and 5.5 min respectively). Among CCMT120404 type cutting inserts, best results in terms of tool life were achieved by applying M1P2 and M2P4 cutting tools (average tool life $T=6.6$ min and 5.8 min, respectively). However, some anomalous vibrations occurred when cutting with M2P4, causing a poor surface quality. Therefore the application of M2P4 is not recommended for machining the considered workpiece material.
SEM and EDS analysis were also performed in order to investigate the tool wear mechanisms. SEM images of primary flank face and rake face of a tested cutting tool are given in Figure 10(a) and Figure 10(b), respectively. Flank wear-land, as well as notches affecting the cutting edge close to the borders of the worn area are clearly visible. Therefore, abrasion is the dominant tool wear mechanism, whereas oxidation can also play an important role. This behavior was expected due to the presence of the highly abrasive Ti(C,N) particles.

![Figure 10. Primary flank (a) and rake face (b) SEM images regarding M2N4 tool](image)

According to Kopac [4] and others, work-hardening can occur when machining Hadfield steel. In this research, the work-hardening on machined surface was present, see Figure 11, since the hardness of the workpiece before cutting was 550 Vickers. Also, it can be seen that the tool geometry did not have a significant effect on the work-hardening.

![Figure 11. Work hardening obtained with the selected tools (95% confidence intervals; measurements executed by Krautkramer durometer).](image)

5. Discussion and conclusions

Good surface roughness ($R_a$<1.9µm) and suitable chip form were obtained in preliminary cutting tests. However, best and most repeatable surface quality was achieved by applying M1N2 and M1P2 cutting tools.

Longest tool lives were obtained by using coated carbide inserts with TiCN+Al$_2$O$_3$ multilayer coating (M1N1,M2N4,M1P2,M2P4). All these cutting tools were characterized by a chamfered cutting edge which strengthened the positive rake face geometry. However, some anomalous vibrations occurred by using M2P4. Therefore, only the other three cutting inserts are most recommended for machining special Hadfield steel with fine dispersion of Ti(C,N) particles.

For a given tool geometry, coating had a significant effect on tool life. Specifically, the presence of TiN in the multilayer structure caused a significant reduction of tool life.

On the other side, for a given coating structure, tool geometry did strongly influence tool life. Specifically, chamfered cutting inserts had longer tool lives with respect to cutting inserts without chamfer.

Strong abrasion and notch wear occurred when turning Hadfield steel.

Relevant work-hardening of machined Hadfield steel was observed after the cutting process. However, the average of micro-hardness was not significantly influenced by tool grade or geometry.

It would be of further interest to investigate different tool materials (coatings) for machining special Hadfield steel with Ti(C,N) particles.

References