Influence of oxygen content on the machinability of Ti-6Al-4V alloy

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Abstract Titanium alloys are widely employed in many aerospace components due to their high strength-to-weight ratio, good corrosion resistance and fatigue properties, maintained at relatively high temperatures. Nevertheless, machining these materials efficiently has become a challenge in a sector that demands high productivity rates and minimal manufacturing times. This work analyses the machinability of the \( \alpha + \beta \) Ti-6Al-4V alloy in rough turning. Since oxygen is one of the elements that most affects the mechanical properties of titanium alloys, the aim is to understand its influence on the machinability of these materials. To do so, two different oxygen contents of 1200 and 2000 ppm are tested. A comprehensive material characterisation of both materials is carried out in order to clearly establish their differences: chemical composition, microstructure and mechanical properties (yield strength and hardness of the phases by nanoindentation). Machining trials consist of (i) tool life tests, which include a tool wear analysis, and (ii) cutting fundamental turning tests, in which the cutting forces and the chip form are studied. The work concludes that Ti-6Al-4V alloy with the highest oxygen content has the worst machinability (~15 % lower compared to lowO), due to its higher volume fraction of \( \beta + \alpha_s \) phase, slightly harder \( \alpha_p \) and greater yield strength, which generates higher mechanical and thermal tool wear. Thus, oxygen is a key composition element that should be controlled in machining titanium alloys, if robust results in tool life are expected to be obtained.

Keywords Titanium alloys · Machinability · Oxygen · Roughing · Tool life · Cutting force

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material characterisation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_\beta )</td>
<td>Beta-transus temperature (phase transition)</td>
<td>ºC</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>True strain</td>
<td>()</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>True stress</td>
<td>MPa</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate tensile strength</td>
<td>MPa</td>
</tr>
<tr>
<td>YS</td>
<td>Yield stress</td>
<td>MPa</td>
</tr>
<tr>
<td>( YS_{0.2} )</td>
<td>Yield stress for a plastic deformation of 0.2 %</td>
<td>MPa</td>
</tr>
<tr>
<td>Machining tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E )</td>
<td>Activation energy</td>
<td>J mol(^{-1})</td>
</tr>
<tr>
<td>( V_b )</td>
<td>Average flank wear</td>
<td>mm</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Clearance angle</td>
<td>º</td>
</tr>
<tr>
<td>( A_c )</td>
<td>Contact area on the rake face</td>
<td>mm(^2)</td>
</tr>
<tr>
<td>( Q )</td>
<td>Cooling flow</td>
<td>l min(^{-1})</td>
</tr>
<tr>
<td>( P )</td>
<td>Cooling pressure</td>
<td>bar</td>
</tr>
</tbody>
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80% of this usage, e.g. blisks for aircraft turbines and ed to this alloy. The aerospace industry accounts for more than 50% of the total titanium production dedicat- compressors.

In recent years, the use of titanium alloys has increased con-

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r_p Cutting edge radius \( \mu m \)
F_c Cutting force \( N \)
V_c Cutting speed \( m \text{ min}^{-1} \)
a_p Depth of cut \( mm \)
d_{peak} Distance between the peaks \( \mu m \)
K_e Entering angle \( ^\circ \)
h_{eq} Equivalent chip thickness (serrated chip) \( mm \)
F_T Feed force \( N \)
f_b Feed per revolution \( mm \text{ rev}^{-1} \)
A Frequency factor in Arrhenius type of equations \( \) MMR Material removal rate \( mm^3 \text{ min}^{-1} \)
V_{c,max} Maximum flank wear \( mm \)
h_{max} Maximum height of the peaks (serrated chip) \( mm \)
V_{c,man} Maximum V_c for a tool life duration of 15 min \( V_b = 0.3 \text{ mm} \)
V_{notch} Notch wear \( mm \)
F_p Passive force \( N \)
\( \gamma \) Rake angle \( ^\circ \)
s Sliding distance \( km \)
K_{sc} Specific cutting force \( N \text{ mm}^{-2} \)
K_{sf} Specific feed force \( N \text{ mm}^{-2} \)
K_{sp} Specific passive force \( N \text{ mm}^{-2} \)
r_t Tool tip radius \( mm \)
h Undeformed chip thickness (continuous chip) \( mm \)
R Universal gas constant \( J \text{ K}^{-1} \text{ mol}^{-1} \)

According to Boyer et al. [7], room temperature tensile properties in titanium alloys are strongly influenced by (i) several microstructural features (such as grain size, grain mor- phology, phase volume fraction and grain orientation), and by (ii) the chemical composition. Mechanical characteristics of titanium alloys depend to a great extent on the content of inevitable gas impurities (O, N, C), which get into the metal from the initial raw material and cause solid solution strengthening. Among the interstitial elements, oxygen is of particular interest because of its high chemical reactivity with titanium at elevated temperatures and its relative high solubility in \( \alpha \) – titanium. In the end use, higher oxygen contents are preferred to increase the strength of the materials. Figure 1 shows that tensile properties in Ti-6Al-4V alloy can be changed approximately 70 to 100 MPa by varying the oxygen content from 1200 to 1800 ppm [8]. In practice, \(~2000\) ppm is the maximum oxygen amount accepted by manufacturers in standard Ti-6Al-4V alloys [7]. In contrast, those with 1200 ppm of oxygen are considered a special grade with extra low interstitials (ELI), which are less frequently employed in the aerospace sector.

There is a strong relationship between the material properties and the machinability of titanium alloys [9, 10]. These works concluded that the heat treatment and the resulting microstructure, which give rise to determined mechanical properties, are closely related to the tool life. However, no practical experiments that account for the influence of oxygen on machinability of titanium alloys have been found in literature.

With regard to the cutting parameters, several research (Fig. 2) have been done to better understand the influence of the cutting parameters on tool life and increase the productivity of titanium components. Significantly, most of the machin- ing tests in titanium alloys are usually carried out in finishing or semi-finishing conditions (MMR<60,000 mm\(^3\) min\(^{-1}\)). Normally, the tests performed with conventional coolant used cutting speeds \( (V_c) \) ranging from 30–100 m min\(^{-1}\), feed rates \( (f_b) \) varying from 0.1 to 0.35 mm rev\(^{-1}\), and depths of cut \( (a_p) \) of 0.3–3.5 mm. In general terms, cutting speeds higher than 60 m min\(^{-1}\) led to rapid tool wear when machining with uncoated carbide tools [11].

Some authors [9, 12] studied the machinability of Ti-6Al-4V at relatively low cutting conditions \( (f_b = 0.1 \text{ mm rev}^{-1}, a_p = 2 \text{ mm}) \), by determining the \( V_{c,max} \) value in single-point turning tests, as suggested by the ISO 3685:1993 (E) [13] standard. This cutting speed is defined as the maximum cutting speed that gives a flank wear value \( (V_b) \) of 0.3 mm after 15 min machining. Hence, the higher the \( V_{c,max} \) the better the machinability of the material. In these research, the \( V_{c,max} \) for Ti-6Al-4V was 80 m min\(^{-1}\).

The criteria to define the end tool life are also described in the ISO 3685:1997 (E) standard. However, from a practical point of view, it seems to be insufficient to describe the tool wear occurring when machining titanium alloys. Machai and