Surface integrity of AISI 4150 (50CrMo4) steel turned with different types of cooling-lubrication

V. García Navas\textsuperscript{a,*}, D. Fernández\textsuperscript{a}, A. Sandá\textsuperscript{a}, C. Sanz\textsuperscript{a}, S. Suzon\textsuperscript{b}, T. Fernández de Mendiola\textsuperscript{c}

\textsuperscript{a} IK4-TEKNIKER/CIC-marGUNE. Polo Tecnológico de Eibar, C/Iñaki Goenaga 5, 20600 Eibar, Guipúzcoa (Spain)
\textsuperscript{b} AL Air Liquide España, S.A. Pº de la Castellana 35, 28046 Madrid (Spain)
\textsuperscript{c} Shuton S.A. Polígono Industrial Goiain, C/ Subinoa 5, 01170 Legutiano, Álava (Spain)

* Corresponding author. Tel.: +34 943 20 67 44; fax: +34 943 20 27 57. E-mail address: virginia.garcia@tekniker.es.

Abstract

Nowadays the use of new high strength alloys is growing, but these alloys are difficult to machine due to the high temperatures generated during cutting. A solution is the use of cutting fluids, but those have adverse environmental effects, health risks and high costs of purchase, storage and maintenance. An emerging alternative is the use of cryogenic fluids such as liquid nitrogen (LN\textsubscript{2}). Nevertheless, in order to accept a new machining process industrially, it must be assured that final structural integrity of the machined part is at least as good as that generated by conventional machining processes. Therefore, in this work it has been compared the surface integrity (roughness, hardness, residual stresses and microstructure) generated in AISI 4150 (50CrMo4) steel by dry turning, turning with lubricant (oil based emulsion) and cryogenic turning with LN\textsubscript{2}. The results prove that cryogenic machining is the best solution since it reduces machining problems of heating, leading to tool life improvement and better surface integrity of turned components.

Keywords: Surface integrity; Cryogenic machining; Lubrication; Cooling; Turning; Residual stress; Hardness; Microstructure; Roughness; Steel

1. Introduction

Current industry demands high technological and operational characteristics to the materials used in their products. Unfortunately, the improvement in performance involves complex machining processes, where the surface integrity of the final products can be adversely affected due to the high temperatures generated during cutting. A solution to this problem is the use of different lubricants and/or coolants.

Nowadays, the use of coolant or MQL (Minimum Quantity Lubrication) systems implies a reduction of tool wear and, therefore, a tool life increase. Furthermore, the use of high pressure in such methods increases the production rate because higher cutting conditions can be used [1]. Hence, the use of cutting fluids facilitate the machining of hardened and difficult to cut materials, but has some limitations because cutting fluids have adverse environmental effects, health risks and high costs of purchase, storage and maintenance.

An emerging alternative is the use of cryogenic fluids such as liquid nitrogen (LN\textsubscript{2}), which can achieve temperatures of -196 \degree C. This emerging technology based on a safe, non-combustible, inert and odorless gas is an infinite resource (78 \% of the air) that has no negative effects on health or the environment.

LN\textsubscript{2} can be used in different configurations aiming to enhance the cutting process, such as pre-cooling the work material, direct spraying towards the cutting zone or as a material surface treatment method. Among the above options, spraying the cutting tool during the
machining process is the method that gives better results of tool life [2]-[4]. Also different designs of tool holders [5] and studies varying the position of incidence of the LN2 have been published [1].

Among the benefits of using cryogenic cooling the following stand out: Cutting temperature is reduced, as several authors, such as [6]-[11], among much others, have observed in cryogenic machining of very different materials, both experimentally and by finite element modeling. Tool wear is reduced and therefore tool life increases, as has been observed by [3],[7]-[11],[12]-[15], among much others. Cutting forces are also reduced, as observed by a high number of authors, for example by [7],[9],[16]-[19], among others.

Therefore, in the literature there can be found a huge amount of works that study the effect of cryogenic cooling on tool life, cutting forces, etc., i.e., the effect in machining performance. Nevertheless, few works can be found where the final surface integrity of the cryogenically machined component is studied. Wang et al. [9] in tantalum and Wang and Rajurkar [4] in several hard-to-cut materials (advanced ceramics, titanium alloys, Inconel alloys and tantalum) have observed that final surface roughness improves when cryogenic cooling is employed in the machining. Bicek et al. [20] and Umbrello et al. [21]-[22] have observed that cryogenic machining results in lower roughness, higher micro-hardness, no recrystallized layers or so called white layers, and a reduction of thermal residual stresses in AISI 52100 bearing steel. Pu et al. [23]-[24] and Outeiro et al. [25] have found that cryogenic machining results in enhanced surface integrity on AZ31B Mg alloy in terms of surface roughness, grain size, crystallographic orientation, hardness as well as residual stresses, which may remarkably enhance the corrosion performance of magnesium alloys. Dhar and Kamruzzaman [26] have observed in AISI 4037 steel that cryogenic cooling provides lesser tool wear, better surface finish and higher dimensional accuracy as compared to dry and wet machining. Finally, Pusavec et al. [27] have observed that cryogenic machining increases hardness and compressive residual stress and reduces surface roughness in Inconel 718.

There is a problematic case in the manufacturing of high precision ball screws, where machining of hardened ball screws with ceramic based inserts produce problems due to the high temperatures generated in the cutting zone. The use of cryogenic cooling could be a way to solve that problem. Nevertheless, in order to accept a new machining process industrially, it must be assured that final structural integrity of the machined part is at least as good as that generated by conventional machining processes. Therefore, in this work it has been studied and compared the surface integrity (roughness, hardness, residual stresses and microstructure) generated by dry turning, turning with lubrication and cryogenic turning with LN2 in AISI 4150 (50CrMo4) steel, a steel used for the manufacturing of ball screws. No previous studies of the effect of cryogenic cooling on surface integrity in this steel have been found in the literature.

2. Experimental procedure

2.1. Material and machining processes

Dry turning, turning with lubrication (oil based emulsion) and cryogenic turning with LN2 on AISI 4150 (50CrMo4) steel have been studied and compared.

AISI 4150 (50CrMo4) steel composition is gathered in Table 1. This material is used in the manufacturing of ball screws. Cylindrical bars of this steel, with initial diameter of 86 mm and 140 mm machinable length have been employed. The initial surface hardness of the bars, prior to machining tests, is 52 HRC.

Table 1. Chemical composition of AISI 4150 steel ( weight %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Others</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>max. 0.4</td>
<td>2</td>
<td>1.05</td>
<td>0.23</td>
<td>-</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The machining of this type of material is made commonly with ceramic tools, so a tool insert with reference SNGN 120716 T01020 with HC2 quality and without any coating has been employed. The cutting conditions employed in all the machining tests are: cutting speed \( v_c = 120 \) m/min, feed rate \( f = 0.18 \) mm/rev and depth of cut \( a_p = 1.5 \) mm.

Machining tests (turning) have been performed in a CMZ Turning Center model TL-15M (5000 rpm, 14 kW). Turning with lubrication is performed with HYSOL XF oil based emulsion. The fluid runs to the tip of the tool through the standard lubrication system installed into the lathe. Cryogenic cooling is performed with an own developed conduction system, shown in Fig. 1, which leads a jet of liquid nitrogen toward the flank of the tool, at a flow rate of 2.19 l/min.

Tool life tests have been performed for each cooling-lubrication condition, i.e. for dry, lubricant and LN2 turning. The criterion for completion of the test (criteria for turning tool life finish) is either breakage of the insert or flank wear (VB) exceeding 0.3 mm, as dictated by ISO 3685:1993. The wear of the cutting tool has been measured with a contact microscope KEYENCE VH-5901.
2.2. Surface integrity characterization

Surface integrity of the machined samples (for the 3 different cooling-lubrication conditions) has been characterized at different stages of the tool life, i.e., for different volumes of material removed.

Surface roughness of machined samples has been measured using a Mitutoyo SJ-201P surface tester.

Surface hardness of machined samples has been measured in a Rockwell Hardness tester using a load of 150 kg.

Surface residual stresses have been measured by means of X-ray diffraction using the sin²θ method. A Bruker D8 Advance diffractometer with parallel beam pollycap, PSD detector and Cr radiation (wavelength λ = 2.291 Å) has been employed for these measurements. Fe-(211) diffraction peak located at 2θ ~ 156º has been used. Surface residual stresses have been measured in the tangential direction of the bars, i.e. in cutting direction.

Microstructural analyses have been performed, on polished and Nital etched cross sections of the components, using a scanning electron microscope (SEM).

3. Results and discussion

3.1 Tool wear

The results of tool life tests are shown in Table 2. In Fig. 2 is gathered the evolution of tool wear in each turning test, with the removed material volume, and in Fig. 3 are gathered some pictures of tool wear in the three machining processes for two different machining times (i.e. two different volume of removed material). Predominant wear during all machining tests is flank wear.

Only in the case of dry turning finish of useful tool life has been reached (tool breakage). In the case of turning with oil-based emulsion (lubricant) useful tool life is nearly finished, since tool flank wear after all the machining tests is 0.232 mm, near the 0.300 mm that indicate finish of tool life, according to ISO 3685:1993. Nevertheless, in the case of turning with LN2, for approximately the same total removed volume of material, tool flank wear is 0.042 mm, much lower than in turning with lubricant, and far from the finish of useful tool life (VB = 0.3 mm).

When turning without any lubrication, i.e. dry turning, serious problems of chip evacuation come about and, as a consequence, insert breakage occurs because of accumulated material in the cutting area. Turning with oil-based emulsion results in a great improvement in evacuation of the machined material. Tool life tests clearly show that cryogenic machining results in an increase in tool life, with lower and more progressive wear, which is a great advantage in the use of ceramic tools. Prolonged tool life can be attributed to a reduction in the temperature dependent tool wear associated to reduced temperatures in the cutting tool. In this line, Dhar et al. [28] attribute the slower increase of flank wear during cryogenic machining to the retention of hardness at the cutting edge because of the stable and intense cooling, which protects the tool from oxidation, corrosion, adhesion and formation of BUE (built up edge).

Table 2. Tool life tests results

<table>
<thead>
<tr>
<th>Cooling method</th>
<th>Total machined length (mm)</th>
<th>Total machining time (min)</th>
<th>Total removed volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>408</td>
<td>4.75</td>
<td>156809</td>
</tr>
<tr>
<td>Emulsion</td>
<td>457</td>
<td>8.35</td>
<td>275818</td>
</tr>
<tr>
<td>LN2</td>
<td>904</td>
<td>9.25</td>
<td>306022</td>
</tr>
</tbody>
</table>

Fig. 2. Evolution of tool life in dry turning, turning with lubricant and cryogenic turning (LN2) of AISI 4150 steel.
workpiece increases too, diminishing the height of feed and, therefore, diminishing the surface roughness. That could be the reason why lower surface roughness has been obtained when turning with lubricant in comparison to LN₂ turning.

It has been measured an increase in surface hardness (Fig. 5) when machining with LN₂ in comparison both with dry and lubricated machining, in agreement with observations of other authors in different materials [20]-25. In dry machining, excessive tool-wear can cause very high temperatures in the cutting zone due to friction, what lead to softening of the machined material. This can be also the reason why higher hardness is obtained in cryogenic machining compared to lubricated turning: tool wear is higher in lubricated turning (Figs. 2 and 3), leading to higher softening of machined material (Fig. 5).

It is observed (Fig. 6) a reduction in surface residual stresses when using LN₂ in turning, as has been also measured by Bicek et al. [20] in AISI 52100 bearing steel. In turning, the force of the cutting tool on the workpiece surface induces local plastic deformation, giving rise to compressive surface residual stresses; on the other hand, high temperatures resultant from friction between tool and workpiece and from the very deformation can generate phase transformations in the most superficial layers as well as tensile residual stresses, both of them detrimental to the service life of the machined part because they promote crack formation and propagation. An increase in tool wear results in higher tool/part friction, leading to higher temperatures and therefore more tensile residual stresses. Therefore, the lower cutting temperatures and reduced tool wear associated to cryogenic machining are the responsible of this better surface residual stress state associated to the use of LN₂ during turning.

In Fig. 7 are gathered some micrographs showing the microstructure in the surface region of AISI 4150 steel after dry, lubricant and cryogenic machining, for a volume of removed material of approximately 50000 mm³. For this volume of removed material tool flank wear is 0.018 mm in LN₂ turning, 0.037 mm in dry turning and 0.070 mm in turning with lubricant, i.e. in all cases the tool is a nearly new tool with flank wear far from tool life end. It is observed that after turning with LN₂ it is not observed any substantial microstructural change, whereas after dry turning and turning with lubricant a surface layer of 1-2 µm thickness with a different aspect, similar to a white layer, appears. This agrees with the observations of Bicek et al. [20] and Umbrello et al. [21]-22] that no recrystallized layers or so called white layers appear in cryogenic machining of AISI 52100 bearing steel. High cutting temperatures and excessive tool wear favor microstructural changes and the formation of white layers [29]-34].
machining results in lower cutting temperatures and lower tool wear, compared to dry turning and turning with lubricant, and that is the reason why after cryogenic machining no white layers (detrimental to the service life of machined components) are formed.

Fig. 4. Evolution of machined AISI 4150 steel surface roughness, Ra (mm), in dry turning, turning with lubricant and cryogenic turning (LN2).

Fig. 5. Evolution of machined AISI 4150 steel surface hardness, HRC, in dry turning, turning with lubricant and cryogenic turning (LN2).

Fig. 6. Evolution of machined AISI 4150 steel surface residual stresses, $\sigma$ (MPa), in dry turning, turning with lubricant and cryogenic turning (LN2).

Fig. 7. Microstructure of AISI 4150 steel after dry turning (a), turning with lubricant (b), and LN2 turning (c) for a volume of removed material around 50000 mm³.

4. Conclusions

Compared to dry turning and turning with lubricant (oil based emulsion), cryogenic machining using LN2 is the best solution to machinability problems of components manufactured using AISI 4150 steel (such as transmission spindles) because of reduced heating problems, leading to tool life improvement and better surface integrity (higher surface hardness, lower residual stresses and no white layers, although surface roughness is a bit worse than with lubricant) of turned components.
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