Numerical simulation of surface modification in dry and cryogenic machining of AA7075 alloy

G. Rotella, D. Umbrello*

*University of Calabria, Department of Mechanical, Energy and Management Engineering, 87036 Rende (CS), Italy
* Corresponding author. Tel.: +39-0984-494820; fax: +39-0984-494673. E-mail address: d.umbrello@unical.it.

Abstract

Functional performance of a machined product is strongly influenced by its surface characteristics that are frequently modified from the process. These changes must be taken into account when modeling the machining process.

This work presents the modeling of grain size and hardness changes induced during turning of AA 7075-T651 alloy using the Finite Element (FE) method. The implemented user subroutine is able to describe the microstructural changes and the dynamic recrystallization in order to correctly simulate the formation of new grains and their influence on the material flow stress. The model is experimentally calibrated and validated to predict the evolution of the surface conditions (grain size, hardness, etc.) when varying the cutting speeds and tool nose radii. All simulations were performed for dry and cryogenic cutting conditions using uncoated carbide tools.

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Selection and peer-review under responsibility of The International Scientific Committee of the “2nd Conference on Surface Integrity” in the person of the Conference Chair Prof Dragos Axinte dragos.axinte@nottingham.ac.uk

Keywords: Machining; Finite Element Method (FEM); Surface Integrity.

1. Introduction

Knowledge about factors that cause microstructural improvements will contribute to a better fundamental understanding of the manufacturing process mechanics and improved knowledge-driven manufacturing process planning, as well as better prediction of the machined component’s lifetime.

Therefore, accurate models, capable of predicting mechanical and thermal behavior, and above all, the surface characteristics of the machined components, are needed in order to obtain feedback information on how to improve the process, and thereby meeting the desired surface and sub-surface property specifications. Consequently, it is useful to have a predictive model for the microstructural changes as a function of the machining conditions [1-3] offering the possibility to save time and money that would be necessary to perform the extensive experiments. To accomplish this, it is deemed necessary to numerically describe the microstructural phenomena involved during severe plastic deformation (SPD) processes, and particularly for metal machining. During turning processes, residual stresses and strain as well as the work-hardening and dynamic recovery occurring during the deformation process can induce microstructural changes on the machined component. This combination of “dynamic” and “static” events needs to be taken into account (i.e. the microstructure drastically changes because the dynamic recrystallization (DRX) occurs due to the total local dislocation density exceeding a critical value). Based on the above current knowledge, this paper reports new findings from an attempt on modeling the machining process to include the effects of cutting speed and cooling conditions on the mechanical, thermal and surface integrity aspects induced by the deformation conditions that exist during turning of AA 7075-T651 alloy. An iterative procedure is utilized for calibrating the constants present in the Zener-Hollomon parameter (associated with grain refinement and material properties) and the Hall-Petch equation (for the hardness evolution) in the investigated materials. Furthermore, the flow stress changes due to the grain size modifications is
also included in the model in order to consider the microstructural effects on the material behavior. Finally, to validate the proposed FE strategy, numerical results are compared with those obtained from previous experiments.

2. Experimental Procedure

Previous experimental evidences [4, 5] have been used to calibrate and validate the model and are here briefly summarized. Dry and cryogenic external turning operations on Aluminum 7075-T651 alloy were conducted on a stiff high speed Mazak QuickTurn 10 CNC lathe. The cutting tools utilized are uncoated carbide tools (KENNAMETAL grade: K313 with a clearance angle of 11° inserts ANSI TPG-432 geometry) with a triangular shape mounted on a CTGPL164C tool holder providing a lead angle of 0°. The tool holder was held in a Kistler 9121 three-component piezoelectric dynamometer for measuring the three cutting force components. The effective edge radius was measured using a Zygo®7300 optical interferometry-based surface profilometer and, the average tool edge radii were around 16\(\mu\)m. The performed tests were carried out at a constant depth of cut of 0.5 mm and feed of 0.1 mm/rev while the cutting speed was varied (180, 320 and 720 m/min). The surface and subsurface hardness values were also measured on a micro hardness indenter. In particular, five hardness measurements were carried out on the surface and at each depth below the machined surface. Each indent was well spaced to avoid interference between each of them (approximately thirty indentations were done along the profile). Finally, all samples were metallographically-processed: sectioned, mounted on a resin holder, and then polished and etched. The etchant employed is the Keller’s reagent that is a chemical recommended for etching nonferrous materials, and especially aluminum. The composition of the reagent is 190 ml of distilled water, 5 ml of Nitric acid, 3 ml of Hydrochloric acid and 2 ml of Hydrofluoric acid. A fresh etchant was used for each sample and the immersion time was around 20 second for each sample. The microstructural changes have been analyzed using an optical Microscope (1000x). In the next sections, the more relevant experimental results are reported and discussed. More details and deeper discussion can be found on prior publications [4, 5].

2.1. Cutting Forces

Figures 1 report the forces generated in the cutting process under dry and cryogenic conditions at varying cutting speed. As shown from the graphs, the force components show a decreasing trend with the increasing the cutting speed, as expected. Furthermore, the main cutting force and the feed force are always higher in the dry conditions.

The reason lies in the higher friction coefficient during the cutting process since although liquid nitrogen is employed to reduce the cutting temperatures and reduce the wear process of the tool, along these directions a small lubrication effect, even though minimal, is produced. In contrast, cryogenic machining produces similar or slight higher radial cutting force for all the employed cutting speed since along this direction the liquid nitrogen produces benefits only on temperature reduction.

2.2. Micro Hardness

The hardness of the bulk material was tested to be 160 HV [4, 5]. All the experimental sets show changes in the surface hardness values, which is commonly seen in machining. Figures 2 shows the hardness variations in selected samples from the machined surface to the bulk material. The results clearly demonstrate that cryogenic conditions allow the material to reach a higher surface hardness and a deeper hardness variation is also noted comparing the results with the dry tests. As shown from Figure 2, dry cutting will generally lead to lower surface hardness.
The reason can be attributed to the effects of low temperatures generated by cryogenic machining, which would reduce the thermal softening effect by reducing machined surface temperature, when applied from the flank side. Furthermore, according to the recrystallization behavior observed, cryogenic coolant also helps to maintain a small grain size after dynamic recrystallization [4, 5] which corresponds to a higher hardness. As a result, cryogenic machining will create a more favorable machined surface in terms of hardness.

In fact, the cryogenic coolant helps to produce a thicker affected layer than dry machining as confirmed by the subsurface hardness measured in each sample (Figure 2).

3. FE Numerical Procedure

3.1. FE model and material flow stress

SFTC FE software Deform 3D® was utilized to simulate the microstructural changes happening during turning of AA7075-T651 alloy. FE 3D modeling was based on the assumptions of a rigid cutting tool (divided into 10000 elements), and an isotropic hardening for workpiece material, modelled as plastic and divided into 50000 elements. Concerning the mesh density, the elements located around the cutting edge and along the machined surface were fifty times as dense as the other ones (average element edge length \( \approx 8 \mu m \)). Workpiece and cutting tool were allowed to exchange heat with the environment; the convection coefficient was selected at 20 W/(m²K), which is the default value for free-air convection in DEFORM (normally it ranges from 5 to 25 W/(m²K)). For the cryogenic machining an environmental window for heat exchange, \( h_{cryn} \), was defined between the machined surface and the flank side of the tool (Figure 4).

As far as the global heat transfer coefficient, \( h_{lat} \), at the tool-chip-workpiece interface is concerned, a constant value of 55000 kW/(m²K) was set in the FE model, according to the guidelines and literature results [2, 6]. In fact, for the investigated cases, considering the workpiece and the tool material used, the setting of this value permits one to reach the thermal steady-state at the tool-chip-workpiece interfaces within a short simulation time by means of the assumption of thermally perfect contact under high cutting pressures. The sticking-sliding friction model (sticking governed by the shear model \( \tau = m \dot{\gamma} \); sliding governed by Coulomb model \( \tau = \mu \sigma \)) have been implemented. Finally, a modified Johnson–Cook (JC) constitutive equation was used to model the material behavior of the AA 7075-T651 aluminum alloy. In particular, the yield stress component
of the JC model is modified in order to take into account the grain size changes as indicated in Eq. (1).

\[
\sigma = \left[ a + \frac{d}{\sqrt{d}} + 310 \cdot e^{3.0} \right] \left[ 1 + 0.002 \ln \left( \frac{d}{\sqrt{d}} \right) \right] \left[ 1 - \left( \frac{T - T_{cool}}{635 - T_{room}} \right)^{\frac{1}{2}} \right] (1)
\]

Where \( T_{cool} \) was set equal to 20°C for dry machining and -182°C for the tests under cryogenic cooling, \( d \) is the predicted grain size, while \( k \) and \( a \) are two constants calibrated from literature [7]. Thus, the flow stress has been firstly implemented by a user subroutine starting from the models proposed by Curle and Govender [7] and Farrokh and Khan [8] and then it has been updated at each step according to the new grain size values.

### 3.2. FE strategy for predicting the grain size and the hardness

An updating strategy was implemented in the FE code to simulate the material’s microstructure changes including the grain size and the hardness variation (Figure 5). In the user routine, Zener-Hollomon equation has been used to predict the dynamic recrystallization and the grain size modification, while the hardness variation has been taken into account in the Hall-Petch equation. Constants \( A \) and \( B \) in the equation of the critical strain, \( \varepsilon_{cr} \), were set as reported in [9, 10]. In contrast, the constants in recrystallized grain and in the Hall-Petch equations were obtained for a test conducted under dry machining since these are material constant and must be identical in any cooling conditions. Details about this calibration can be found in [11]. Applying this methodology to the proposed FE model which incorporates the new flow stress that is constantly updated with the new grain size, the calibration constants can be calculated. The effects of the modified JC are evident when calibrating the constants for the iterative procedure.

#### 3.3. FE calibration

The calibration process of the FE model for dry and cryogenic machining of AA 7075-T651 aluminum alloy is shown in Figure 6. The values of the friction coefficients were determined through an iterative calibration process taking into account prior results [11], and some preliminary numerical simulations on the cutting forces prediction. According to that, the friction values (\( m \) and \( \mu \)) to be set in the FE models were: \( m = 0.9 \) and \( \mu = 0.6 \) in dry machining; \( m = 0.88 \) and \( \mu = 0.58 \) in cryogenic machining. The coefficient, \( h_{cryo} \), to be set in the local environment window to simulate the cryogenic cooling effects was firstly set equal to 0.2 kW/(m²K) as suggested by Lee et al [12], then it was calibrated through another iterative process using the some cutting forces data from cryogenic machining.

### 4. FE Validation and FE Analysis

After the calibration phase, the FE model has been validated by comparing the experimental data with other corresponding simulation results. Figures 7-9 show the comparison between the measured and the predicted forces for dry and cryogenic machining. The predicted principal cutting force trend (Figure 7) is always aligned
with the one found in the experiments; also the error is low, (i.e. the higher error was ranging between -9% to +8% for test at 180 m/min under cryogenic and dry condition, respectively). Figure 8 and 9 show that even the radial and feed forces trend is correctly predicted although in some cases a discrepancy can be noted, especially under cryogenic machining. These discrepancies might be related to the friction models used which are well tested in orthogonal machining, but they are not yet for 3D machining. In fact, other important parameters must be taken into account and related to the friction coefficient as the tool geometry (tool nose radius, angles, etc.) and the grain size. Figure 10 shows a steady-state step of the FE simulation at 320 m/min showing the predicted grain size and the surface hardness modification during cryogenic machining. As it can be seen, the implemented user routines leads to get stable and almost uniform data prediction unless the transient phase where cutting forces and temperature are still not stationary.

In fact, it is worth to point out that, due to the numerical simulation setting, only the region with a proper mesh configuration (element size and mesh box) can be taken into account when extracting the results from the code. In particular, the region influenced by the tool contact cannot be considered as well as the region outside the mesh box as shown in Figure 11. The relevance of the proposed FE strategy is proven by the good agreement in the prediction of both grain size (Figure 12), and the surface hardness on the machined workpiece (Figure 13) for each validation test. In fact, a very small discrepancy is noticed between the predicted and the experimental values of hardness and grain size for AA 7075-T651 alloy. In particular, machining under dry condition (Figure 12) is slightly less accurate than the cryogenic one. However, in both cases, the differences between predicted and experimental values are lower than the 7%.
As far as the grain size trend is concerned, higher refinement (i.e., smaller size) with increasing of cutting speed, is due to a larger Zener–Hollomon parameter as a consequence of higher strain-rate and slightly higher temperature near to the shear zones. These observations are in agreement with those observed by Tsuji and Maki [13] regarding the relationship between dynamically recrystallized grain size and the Zener–Hollomon parameter. However, what is important to point out is that the cold flow in cryogenic machining allows the process to generate lower grain size since it reduces the regrowth phase keeping the grain size smaller after DRX. This finding permits one to conclude that, although in cryogenic machining the temperature along the shear zones is slight lower (then bigger grain size should be expected), its ability to stops the regrowth phase after DRX plays the major role in the grain refinement. Finally, a very good agreement was also found in the prediction of the surface hardness on the machined workpiece for all the tests (Figure 13). These accurate results can be surely attributed to the fact that prediction of the surface hardness was carried out by using the Hall-Petch equation in combination with the modification of the flow stress due to the new grain size. Particularly it was found that both the cutting speed and cooling conditions influence the machined surface and subsurface integrity since both dynamic recrystallization and higher hardness values were observed.

Acknowledgements

The authors gratefully thank the Institute for Sustainable Manufacturing, ISM, at the University of Kentucky, for allowing to use the experimental equipment and Prof. I.S. Jawahir and Prof. O.W. Dillon Jr. for their comments and help. The authors gratefully acknowledge the help provided by T. Lu and C. Arvin during the experimental work conducted at the ISM. The students G. Cugliari, G. Durante and M.R. Ussia (University of Calabria) are also acknowledged for their contribution with the FE analysis.

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