Impact of superfinish turning on surface integrity of pure copper

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Abstract

The presented study deals with comprehension of relationships between machining cutting conditions and physical-chemical properties linked with surface integrity. A multi-physics model is presented to calculate residual stress, temperature and dislocation fields in the machined material. This model includes both thermal-mechanical, structural evolution and dynamic recrystallisation approaches. The model was applied to pure copper after superfinish turning. Good agreement was found between numerical values and experimental ones. This paper also presents a work on the impact of mechanical and microstructural changes induced by machining on the electrochemical behaviour and corrosion resistance.

Keywords: Superfinish turning, Surface integrity, Corrosion resistance.

1. Introduction

Machining introduces residual stresses [1] at the part surface and can modify the microstructure near the surface. Numerical models have simulated the chip formation, the tool/chip interactions [2] and the material removal operation [3]. Others [4-5] predicted the residual stress field in the part. Experimental studies have quantified the influence of the main cutting conditions on the surface roughness [6], residual stresses [7], microstructure [8] and texture [9]. By contrast, dynamic effects, including recrystallisation and phase transformation, have rarely been investigated [10]. Studies have established that the microstructure of pure copper is affected by dynamic recrystallisation (DRX) in the machined chip. Observations demonstrated that these modifications also occur in a volume close to the machined surface [10] and take place during the thermal-mechanical processing of engineering materials.

Here, the multi-physics model includes a thermal-mechanical approach (providing stress, strain and temperature fields), a structural evolution approach (Evolution of Defect Density giving the dislocation

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density) and a dynamic recrystallisation approach to predict material properties after superfinish turning, taking into account metallurgical phenomena operating at high strain rates.

2. Multi-physics Model

2.1. Principle of the multi-physics model

Fig. 1 presents the steps of the model for calculating strain, stress, temperature and dislocation fields.

The part was assumed to be semi-infinite, homogeneous and isotropic with linear hardening and to deform in a plane-strain manner. The mechanical formulation of the model was then restricted to a plane \((x_1, x_2)\) [Fig. 2(a)]. It was also assumed that deformation of the part was continuous and steady. All quantities were referred to the part coordinate system shown in Fig. 2(b).

2.2. Constitutive equations

Analytical expressions were considered to calculate the residual displacement field generated after superfinish turning [5]. Note that these expressions were developed from experimental observations [11]. They are valid in the vicinity of the cutting tool. The residual strain components, \(\varepsilon_{11}, \varepsilon_{22}\) and \(\varepsilon_{12}\), were analytically calculated from the displacement field and the small-strain theory. The residual stress components, \(\sigma_{11}, \sigma_{22}, \sigma_{33}\) and \(\sigma_{12}\), were then derived from the Von Mises criterion with isotropic hardening. Values of the stress components were calculated at each node of the mesh. Elastic correction was then applied to fulfil equilibrium conditions [5]. The temperature field \(T(x_1, x_2)\) was numerically calculated from the genuine energy equation which can be expressed as follows

\[
\rho_{Cu} C_{Cu} \frac{DT}{Dt} = k_{Cu} \left( \frac{\partial^2 T}{\partial x_1^2} + \frac{\partial^2 T}{\partial x_2^2} \right) + \beta W^{pl} (1)
\]
In Eq. (1), \( \rho_{Cu}, C_{Cu}, k_{Cu} \) are the density, the specific heat and the thermal conductivity of pure copper. \( \beta \) is the Taylor-Quinney coefficient representing the fraction of plastic work, \( W^{pl} \), transformed into heat (usually, \( \beta = 0.9 \) for FCC materials).

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The dislocation density was then obtained using the following differential equation of structural evolution (called Evolution of Defect Density, EDD) [12]:

\[
\frac{\partial \rho}{\partial \varepsilon} = M_H(\varepsilon) - k_a(\varepsilon, T).\rho 
\]

(2)

where \( k_a \) is the rate-and temperature-dependant annihilation function and \( M_H \) is the rate-dependant multiplication function. In the case of monotonous loading paths, these two functions are constant [13].

Solving Eq. (2) gives an expression of the dislocation density vs. equivalent strain:

\[
\rho = \rho_0 \cdot \exp(-k_a \varepsilon) + \frac{M_H}{k_a} \left[1 - \exp(-k_a \varepsilon)\right]
\]

(3)

where \( \rho_0 \) is the initial dislocation density. Eq. (4) represents the dislocation density contribution to the equivalent stress:

\[
\sigma = F \cdot \alpha \cdot G \cdot b \cdot \sqrt{\rho}
\]

(4)

In Eq. (4), \( F \) is the geometrical Taylor factor, \( \alpha \) is the coefficient of dislocation/obstacle interaction, \( G \) is the shear modulus and \( b \) is the magnitude of the Burgers vector. A relationship between equivalent stress and equivalent strain could then be proposed. To determine numerical values of \( \rho_0, k_a \) and \( M_H \), shockloading tests were performed on cylindrical samples using a Hopkinson bar apparatus.

Then, metallurgical changes induced by dynamic recrystallisation processes are studied. The presence of both high temperatures and high dislocation density may activate dynamic recrystallisation (DRX) processes, which induces a refinement of the material microstructure [10]. In the case of homogenous materials, recrystallisation occurs for \( f = 1/2 \) [14], where \( f \) is the volume fraction concerned by the DRX process. The dislocation density was expressed as a function of applied temperature \( T(x_1, x_2) \) and time \( t \), where \( A, g_0, f_0, \rho \) are experimentally determined DRX model parameters and \( Q \) is the activation energy.

\[
\rho = \frac{1}{A^{\frac{1}{kT \cdot \ln(t, f) - 3Q}}}
\]

(5)
Recrystallisation occurs in a region where the dislocation density calculated from the DRX approach is smaller than the value obtained from the EDD approach \( (\rho_{DRX} < \rho_{EDD}) \), as shown in Fig. 3. Therefore, the recrystallisation layer thickness was estimated at the depth \( h_{recrist} \) where \( \rho_{DRX} = \rho_{EDD} \).

![Activation of dynamic recrystallisation](image)

Fig. 3: Schematic representation of the determination of the recrystallised thickness by considering the evolutions of the dislocation density vs. depth derived from the DRX and EDD approaches.

3. Experimental

3.1. Experimental set-up

Experiments were conducted on copper OFHC with high purity and no phase shift. Samples were machined under longitudinal turning conditions, as represented in Fig. 2 (a). Eight cutting conditions were considered: the machine tool quality, the tool nose radius, the edge sharpness, the length of the tool holder, the cutting speed, the depth of cut, the feed rate and the lubrication. For each condition, two levels were chosen and an orthogonal plan \( L_{16} \) designed according to the Taguchi’s method was considered. Sixteen samples were prepared. The chosen values for cutting velocity were: \( V_c = 138 \) m/min and \( V_c = 86 \) m/min for nominal and irregular cutting conditions. Feed rate values were \( f = 0.05 \) mm/rev and \( f = 0.2 \) m/rev. Carbide insert tools were used with two different tool nose radii: 0.4 mm and 0.8 mm. Depth of cut values were between 0.05 mm and 0.3 mm. Tool inserts were mounted on two tool holders with different geometry to investigate the influence of the overhang and their vibrational properties. "New" or "used" cutting edge allows considering the sharpness of the edge and tests were conducted with or without lubricant. In addition, two different machine tools were used: a CNC lathe and a classic lathe. This allows investigating the effect of machine tool rigidity on surface properties.

3.2. Results and discussion

Surface observations after machining tests gave values of surface and subsurface characteristics for the sixteen samples. The measured responses are: the affected layer thickness \( A_t \), the roughness criteria \( R_z, F_2 \) and ODF texture indexes and the quadratic stress \( \sigma_{quad} \). A regression analysis was performed to compare the influence of cutting parameters on the considered responses. It has been shown that:

- the affected layer thickness depends on the feed rate, the tool nose radius and their interaction;
- the surface roughness was modified by the feed rate, the edge sharpness and the tool nose radius;
- the quadratic stress is affected by the machine tool, the lubrication and the edge sharpness;
- the crystallographic anisotropy was mainly governed by the feed rate and lubrication;
- considering cumulative effects, it appears that the most influential cutting parameters are the feed rate, the lubrication, the edge sharpness and the tool nose radius.

The texture indexes vary significantly and samples machined with the feed rate of 0.2 mm/rev (highest value in this study) show systematically a shear-type texture [15]. By contrast, most of the pole figures determined on the other samples (feed rate of 0.05 mm/rev) reveal the same crystallographic orientation as the material bulk. The Pearson’s correlation matrix [16] was calculated to quantify the degree of linear relationship between surface and subsurface characteristics. No correlations were observed between quadratic stresses and the other characteristics. By contrast, the affected layer thickness and the roughness were highly correlated (correlation factor of 0.93), indicating that they increase together linearly. This
was confirmed by plotting the affected layer thickness vs. the roughness, as shown in Fig. 4. The quantitative relationship in Eq. 6 was then proposed.

\[ A_t (\mu m) = 1.36 \times R_z (\mu m) + 1.03 \] (6)

Therefore, the affected layer thickness could be calculated from the roughness values which are obtained from non-destructive methods with, in this case, an error of about 2.5 \( \mu m \).

![Fig. 4: Linear relationship between the roughness \( R_z \) and the affected layer thickness \( A_t \).](image)

Observations at the microscopic and nanoscopic scales showed a layer with a modified microstructure compared to the bulk structure. Numerous grains of nanometric size without preferential direction and macles have been observed in some grains. This confirms that a microstructural transformation took place and conducted to a refined structure: the material can recrystallise in the subsurface.

3.3. Comparison between experimental and numerical results in the case of turning

The multi-physics model was applied to machined samples of pure copper. The highest stress values were found at the machined surface and no stress was measured in the material bulk. The dislocation field was calculated according to the EDD approach, giving a value of \( \rho = 5.07 \times 10^{14} \text{ m}^{-2} \) in the machined sample and \( \rho_0 = 4.2 \times 10^{13} \text{ m}^{-2} \) in the bulk. These results were validated by means of nano-indentation tests. The evolution of the dislocation distribution shows very good agreement with the distribution obtained from the multi-physics model. The recrystallisation layer thickness \( h_{\text{recrist}} \) was estimated by considering the dislocation distributions and a value of 20\( \mu m \) was found. Nearly the same value \( h_{\text{recrist}} = 22.7 \pm 9.5 \mu m \) was measured from optical images of cross-section surfaces.

A good agreement was obtained between experimental and numerical results, also for stress values, dislocation field and affected layer thickness.

4. Surface integrity

4.1. Local electrochemical behaviour of machined surfaces

The influence of surface characteristics on the local polarisation curves of surfaces in 1M NaClO\(_4\) was investigated at the micro-scale using the electrochemical micocell technique. The cathodic branch of the polarisation curves was generally not affected by the machining operation. By contrast, the shear-type crystallographic orientation generated under certain machining conditions tends to stabilize the material in the presence of an aggressive solution by inhibiting anodic reactions. This beneficial effect was counter-balanced by the deleterious impact of roughness and/or quadratic stress. In the presence of lubrication, the current densities determined in the passive range were generally very low. It appears that the current density in the passive range increases linearly with quadratic stress and a quantitative relationship was found between two parameters. The evolution of the open-circuit potential which is an important parameter describing the electrochemical behaviour of the specimen surface under free corrosion conditions was analysed. The obtained results indicate that the open-circuit potential is shifted...
in the anodic direction with increasing quadratic stress, microroughness and lubrication. In the future, the pitting corrosion leading to significant damages will be proposed.

4.2. Salt fog exposure tests

Several machined parts were exposed to a salt-fog atmosphere generated from 0.1M NaCl solution with a pH 6.5. To assess the reproducibility of results, two identical samples were put in the test chamber at different locations. Salt fog was generated by an ultrasonic humidifier and injected from the top of test chamber at rate of 7 mL/h. During this test, liquid droplets are observed at the specimen surface and atacamite is formed. After 2200 hours, the percentage of surface covered by this oxide varies significantly, between 12% and 27%. This result confirms that surface characteristics play an important role in corrosion processes. Statistical analysis based on the Pearson's matrix indicates that the most influent surface characteristics are the residual stresses, lubrication and surface roughness. Low values of the surface roughness promote the stability of droplets. When atacamite formation proceeds, pH decreases in the droplet, promoting dissolution of copper. After removing atacamite in alcohol under ultrasonics, significant damage of the matrix was found. Holes with a depth of 20 μm and integrangular corrosion were observed.

This study confirms that machining affects the surface and subsurface characteristics of pure copper. Such changes may have significant impact on the physical-electrochemical behaviour (corrosion resistance, for instance) of parts [17].

References

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