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On the optimization of the cutting conditions for an improved corrosion resistance of OFHC copper

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Abstract

Machining has a particular impact on the surface integrity and on corrosion resistance of components. In fact, material removal induces geometrical, mechanical and micro-structural modifications in the machined surface and sub-surface that alter the electrochemical behavior of the material, and so the aging process. In this study, oxygen free high conductivity copper (*OFHC*) has machined under orthogonal cutting conditions using uncoated cemented carbide tools. Then, the corrosion resistance in 0.1 M NaCl salt fog atmosphere of the machined samples is analyzed. Finally, the optimal cutting conditions, including the tool geometry, for an improved corrosion resistance are identified. Their influence on the surface integrity, and then their consequences on the surface aging response is discussed.

Keywords: Surface Integrity; Corrosion Resistance; OFHC copper; Orthogonal cutting; Machining.

1. Introduction

Sustainability, functional performance and life of components present the core of nowadays research in pioneering mechanical industries. Manufacturers seek the control of the surface integrity of their produced components in terms of topological, mechanical and metallurgical states [1,2], in order to guarantee the part quality and prevent any failure. One way to achieve it is the optimization of the machining conditions. Consequently, the surface integrity will be affected, and so the functional performance and life of the machined component as well [3,4], including fatigue life and corrosion resistance. Concerning the corrosion resistance of the machined surface, several studies have shown that it strongly depends on the surface integrity. Bissey-Breton et al. [7] found that surface roughness and surface residual stresses are highly correlated with the free corrosion potential, when compared to other surface integrity parameters. Robin et al. [8] found that the corrosion resistance of copper decreases with the strain intensity induced by the swaging process. Yin et al. [9] showed also that the initial grain size, grain boundaries and twins have an impact on the in-depth residual stresses distribution which affects corrosion wear of copper surfaces when exposed to NaCl solution.

This paper studies the influence of the cutting conditions, including tool geometry, on the surface integrity and corrosion resistance in salt fog atmosphere of oxygen free high conductivity copper (*OFHC*). The optimal cutting conditions are identified and explained basing on their impact on the surface integrity and its consequence on the surface electrochemical response ruling the aging.

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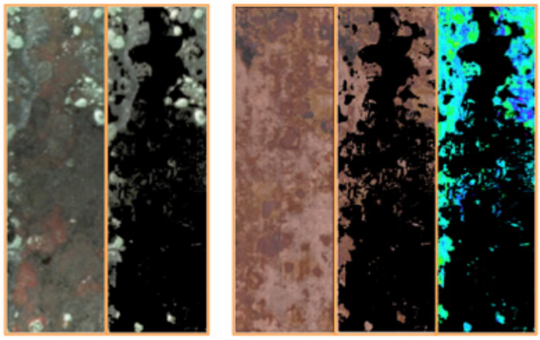
2. Procedure for surface integrity analysis

Orthogonal cutting tests in planing configuration were performed on flat specimens (40×15×4 mm) of *OFHC* copper (annealed at 450°C for 2 hours, with an average grain size of 55 µm), using a *DMG DMC85V* milling machine. Uncoated cemented tungsten carbide cutting tools (*M10* grade) with 4 different geometries were used. All tool geometries were characterized by a constant edge radius (r_n) of 10±2 µm, but different rake angle values (γ) of 20° and 30°, besides two flank angles (α) of 5° and 10°. Two uncut chip thicknesses (h) values of 0.05 and 0.2 mm were used. The cutting speed (V_c) and the width of cut (W) was kept also constants and equal to 90 m/min and 4 mm, respectively. Low temperature pressurized air (-5±2°C; 6 bar) cooling generated by a vortex system was applied to minimize the adhesion phenomenon between the tool and the work material. Residual stresses were determined using *PROTO™ IXRD* diffractometer, based on the X-ray diffraction technique and applying the $\sin^2\psi$ method. According to this method, the residual stresses were calculated from strain distribution $\varepsilon_{\varphi\psi}\{hkl\}$ derived from the measured inter reticular plane spacing and knowing the elastic radio crystallographic constants, $S_1\{hkl\}$ and $½S_2\{hkl\}$, which are equal to -3.13×10^{-6} MPa^{-1} and 11.79×10^{-6} MPa for *OFHC* copper, respectively. An X-ray Mn-Kα radiation (18 kV at 4 mA) was used to determine the elastic strains in the (311) planes (149.09° Bragg angle). Residual stresses were determined in the machined surface, in the cutting direction and parallel to the cutting edge. To evaluate the dislocation density, a measurement of the Bragg peak broadening of the dislocation/defect density in the diffracting domain by X-ray diffraction was performed. In fact, for a simple Gaussian distribution, the full width at half maximum (*FWHM*) may be related to the dislocation density (ρ) when the model of Williamson and Smallmann [10] is used. The grain size measurements were performed using the optical microscope *OLYMPUS™ BX51M* after an electro-polishing with phosphoric acid to reveal the grains boundaries using *Struers™ LectroPol-5* machine. Finally, to measure the arithmetic roughness (S_a) and the roughness at maximum height (S_t) of the machined surfaces, the interferometer *Wyko*™ *NT1100* was used in VSI mode (Vertical Scanning Interferometry) having a resolution of 2 nm in the field of measurement.

3. Procedure for aging in salt fog atmosphere analysis

The object of corrosion tests under salt fog atmosphere is to follow the evolution of the machined surfaces aging in a corrosive environment. The specimens of the machined *OFHC* copper were put into a salt fog chamber containing 0.1 M NaCl at a continuous flow of 9 mL/h at 24 ± 1°C for 2700 hours. At each specific moment of the aging time, specimens were taken in photos to calculate the evolution of the oxidized surface. The lightening with white light was controlled, and the camera was fixed in order to keep natural colors and net shape photos. Those images were filtered to isolate the studied surface from the redundant parts of the specimen surface corresponding to the edges and tool stabilization area. The calculus of the percentage of green inside the surface was done using scripts developed with *Matlab®* software. After the aging tests, the volume of copper participating into the oxidation reaction per mm^2 covered by atacamite (the green color) was quantified. In fact, the oxidized surface was taken in photo by a high-resolution microscope *Keyence*™. Then, the surface was cleaned from oxides and taken again into photo. The topography was measured by optical microscope *Alicona*™ using the variation of focal distance technique. The volume of *OFHC* copper that disappeared from the oxidized surface was calculated by treating automatically the images under *Matlab®* (cf. Figure 1) using a script developed for the study making the following tasks:



(a) (b) (c)

Fig. 1. Evaluation of the volume of copper dissolved by mm^2 covered by atacamite.

a) Isolation of green zones (covered by atacamite) starting from a photo of the oxidized surface as shown in Figure 1a.
b) Starting from the image of the cleaned surface, isolating topographies of zones corresponding to those covered by green before the cleaning as shown in Figure 1b.
c) Visualization of the topography corresponding only to the filtered zones as shown in Figure 1c. Level 0 corresponds to the mean plan of the freshly machined surface, before the aging test (R_a < 800 nm).
d) The program calculated the volume of copper that has removed (valleys) under the zones previously covered with atacamite, and divided it by the green analyzed surface, which gave a mean value of the depth of the dissolved substrate.

4. Results and discussion

Figure 5 shows a non-negligible influence of the cutting conditions in on the evolution of the corrosion of *OFHC* copper surfaces, especially after 700 hours. under saline atmosphere. In fact, for the surfaces generated with a tool having the same rake angle of 20°, a raise in the uncut chip thickness accelerates the corrosion (cf. Figure 2). Nevertheless, this phenomenon is not seen when the rake angle is 30° where the uncut chip thickness seems to have no influence. On the other side, whatever the rake angle and the uncut chip thickness are, the raise of the flank angle from 5° to 10° shows a better influence on corrosion resistance. As observations are not enough to reveal the existing relationships between the cutting conditions and corrosion resistance, further analysis is needed to reveal their impact on the surface integrity responsible for this behavior.

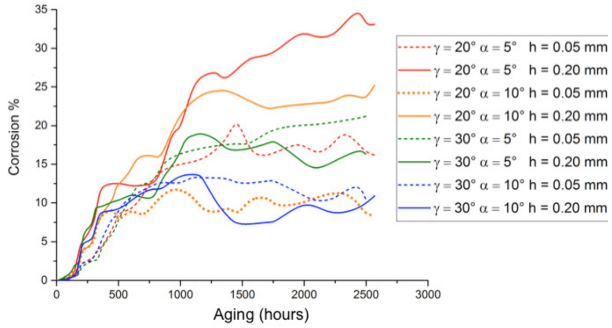


Fig. 2. Corrosion evolution under saline atmosphere for surfaces obtained by orthogonal cutting at V_c = 90 m/min.

To explain degradation under the green surface, in-depth topography is measured under the oxide once it is removed. The removed volume per surface unit reflects the mean in-depth degradation under the oxide. Results are represented in Figure 3.

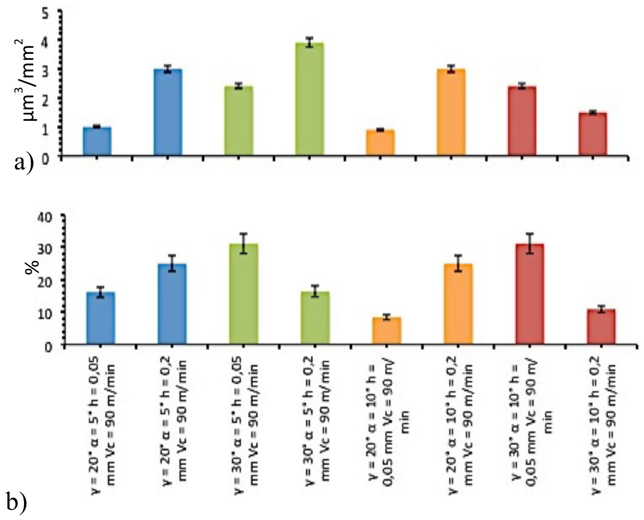


Fig. 3. (a) Mean in-depth degradation induced by oxidation at the end of the aging test under saline atmosphere, and (b) percentage of the oxidized surfaces at the end of the aging test under saline atmosphere.

Comparing the percentage of oxidized surface at the end of the aging test under saline atmosphere (cf. Figure 3b), the following remarks can be drawn: i) The least covered surface by atacamite is the least damaged under the green oxide (γ = 20°; α = 10°; h = 0.05 mm; V_c = 90 m/min); ii) The most covered surface by oxides is not necessarily the one knowing the worst in-depth degradation (γ = 30°; α = 5°; h = 0.05 mm; V_c = 90 m/min).

A unidirectional profile measured in the oxidized region was taken from every analyzed surface to identify the shape profile under the oxide. It was measured only under the green areas (represented by the green lines in Figure 4 as an example). The used in-depth resolution is 78 nm and the horizontal resolution is 5 µm. According to the obtained profiles, it is remarkable that under the green areas two types of cavities can prevail: large cavities with plate valleys (corresponding to generalized dissolution, cf. Figure 4.a) and thin and deep cavities (corresponding to intergranular corrosion cf. Figure 4.b) in the borders of the green area.

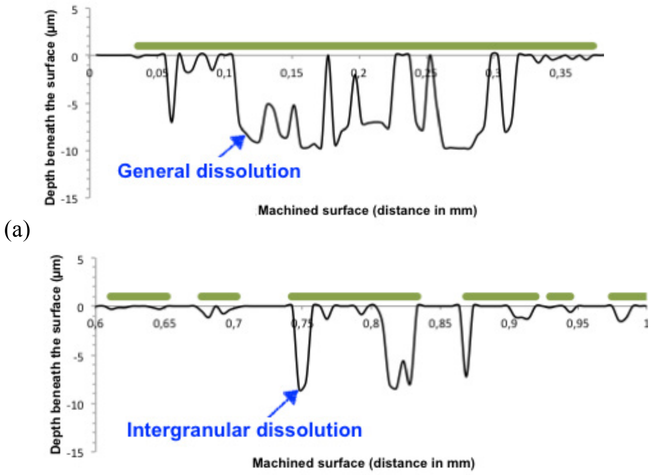


Fig. 4. Profiles under the green zones for surfaces obtained by the conditions γ = 30°, α = 5°, h = 0.2 mm and V_c = 90 m/min. Part of the analyzed profile presenting generalized dissolution (a) and intergranular corrosion (b).

The cavities depth varies under the surfaces covered by the green oxide, what witnesses a non-uniform dissolution happening on the same surface. These observations under the oxides allow the corrosion process analysis explaining the surface damage in the presence of saline atmosphere as follows [12]. Inside the droplets, copper dissolution leads to the formation of the ions Cu^+ or Cu^{2+} in aqueous solution. Associated to anions Cl^- already present in the droplet, they constitute the green compound CuCl. With high chloride concentration, they can even produce the ions of $CuCl^{2-}$. On the other side, cations Cu^{2+} can be hydrolyzed to form atacamite $Cu_2(OH)_3Cl$. This reaction, consuming molecules of H_2O, produces protons H^+, decreasing the pH. As the droplet stagnates in the surface, the pH diminishes with the generation of atacamite. A previous study [11] has demonstrated that pH lower than the limit of copper dissolution can be rapidly reached leading to a generalized dissolution and to intergranular corrosion. The electrons issued from the dissolution reduce the oxygen inside the droplet. As the solubility of oxygen inside water is high, the cathodic reaction continues, and the dissolution evolves into cavities. Then, what makes a machined surface more active than the other just by manipulating the cutting conditions?

To answer that question, the relationship between the surface integrity parameters (surface residual stresses in the cutting direction σ_x and in the transversal direction σ_y, the roughness S_a and S_t parameters, the grains size d_{grain} and the dislocations density ϱ, all detailed in Table 1) and corrosion in terms of the oxide surface area and the surface in-depth degradation are evaluated using the correlation of Pearson technique. The results (cf. Figure 5) show that concerning to the area of the oxide surface is highly sensitive to the grain size d_{grain}, then to the surface roughness S_a, while in-depth degradation is mostly related to the residual stresses. In fact, the preferential dissolution starting sites are the grains boundaries and the peaks of roughness presenting micro-electrodes. So, more grains and more peaks imply greener surface. However, when it is up to the in-depth degradation, tensile stresses will play the major role in continuing and accelerating the dissolution process [12].

Table 1. Results of the surface integrity (SI) analysis.

γ °	α °	h mm	σ_x MPa	σ_y MPa	S_a nm	S_t μm	d_{grain} μm	ρ μm/μm³
20	5	0.2	106	81	626	17.4	7.7	32
30	10	0.05	134	118	672	31	14	1080
20	5	0.05	181	145	471	22.6	5.4	1260
30	10	0.2	59	50	662	15.3	6.1	425
20	10	0.2	-10	9	677	16.9	7.1	29
30	5	0.2	36	41	461	20.9	5.2	355
30	5	0.05	204	105	440	18.8	3.1	1320
20	10	0.05	206	130	550	5.7	8	92

As S_a, d_{grain}, σ_x and σ_y are the surface integrity parameters identified as the most relevant in this study of the machined surfaces corrosion according to Pearson's correlation coefficients, the analysis of variance *ANOVA* revealed their relationship with the tested cutting conditions via Fisher indexes, as shown in Table 2. The highest Fisher index related to the roughness S_a is attributed to the flank angle α. In fact, unlike the turning operation where the combination of tool geometry and cutting parameters (in particular the feed) generates feed marks, in orthogonal cutting the machined surface is theoretically flat. However, small tool flank angle generates more friction between the tool flank face and the machined surface, resulting into build up and micro-tearing in the later. As a consequence, the value of S_a raises. Concerning to the residual stresses they are clearly driven by the uncut chip thickness. Indeed, while raising the uncut chip thickness, the residual stresses resulting from the mechanical loading cycle are more tensile [13]. However, concerning to the grains refinement, the impact of the cutting conditions is more complicated, as this phenomenon seems to be sensitive to the interaction of the different parameters.

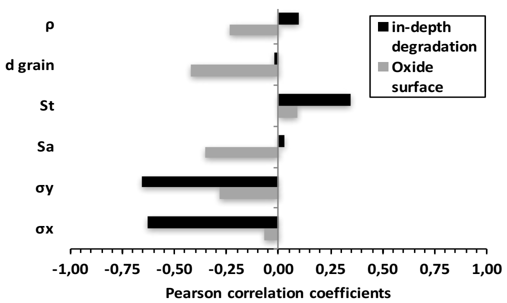


Fig. 5. Pearson correlations between the surface integrity measured parameters and the in-depth degradation and oxide surface at the end of the aging test in salt fog atmosphere.

Table 2. Fisher indexes resulting from the analysis of variance *ANOVA* between the cutting conditions and the S.I. parameters.

	γ	α	h	h*α	h*γ	α*γ
S_a	0.1	6.6	1.5	0.1	0.6	3.2
d_{grain}	0.2	2.2	0.7	2.5	0.3	2.6
σ_x	0.6	0.5	20.6	0.7	0.0	0.0
σ_y	1.2	0.2	15.8	2.3	0.0	0.3

5. Conclusion and outlook

In this paper, the influence of the uncut chip thickness, tool rake and flank angles on corrosion resistance of *OFHC* copper surfaces obtained by orthogonal cutting in 0.1 M NaCl salt fog atmosphere is investigated. To explain the observed phenomena, surface integrity induced by the cutting process, in particular the surface topography, the surface residual stresses, the grains size and dislocations densities are experimentally studied. Their relationship with, from one side, the corrosion aspects and, from the other side, with the cutting conditions, are statistically revealed using Pearson's correlation and *ANOVA*, respectively.

To slow down the corrosion process, first the surface roughness should be minimized by reducing the friction at the flank face by increasing the tool flank angle. Then, the formation of small grains at the machined surface should be avoided as the grain boundaries promote sites for dissolution. The statistical analysis has shown that the interaction between the different cutting parameters has an influence on dissolution evolution, and the best cutting conditions identified with the smallest area covered by atacamite is: γ = 20°; α = 10°; h = 0.05 mm when V_c = 90 m/min.

To minimize the in-depth degradation under the green surface and avoid the general dissolution, the priority is making the residual stresses more compressive or less tensile, by applying low uncut chip thicknesses minimizing the mechanical loading, and so the stresses. The optimal conditions among the tested one are the same as the above-mentioned. As the degradation manifested into deep intergranular dissolution or general dissolution presents a favorable condition for cracks and failure, it is worth to prevent it. Indeed, the machining conditions should be wisely chosen, especially when corrosion impacts the functional performance and life of the component into its working environment.

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