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Understanding the Formation of Nano and Micro Particles During Metal Cutting

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Abstract: Respiratory diseases caused by the inhalation of metallic particles become a serious problem. In previous research we presented experimental studies on the effects of cutting speeds, workpiece material and tool geometry on dust emission during dry machining. To limit dust emission, we must understand under, which conditions it is formed and be able to predict it. In this study, the origin and the mechanisms of particle emission are identified. The explanation of the origin of the particle emissions is based on phenomenological aspects: Energy approach combined with the friction and the plastic deformation of the workpiece material. The chip morphology is investigated to assess its effect on particle emission. The materials tested are 6061-T6 aluminum alloy, AISI 1018, AISI 4140 steels and grey cast iron during an orthogonal turning process.

Key words: Machining, dust, nanoparticles, friction, stacking fault energy

INTRODUCTION

Epidemiological studies prove that the exposure to high concentrations of inhalable metal particles can cause serious pulmonary disease. Aerosols generated during machining processes are harmful both to operator health and to the environment (Dhar *et al*., 2006). The aerosols can have a solid or liquid form. The solid aerosols produced during machining come from the part material, while the liquid aerosols is caused by the impact of cutting fluids on workpiece material or tooling (Yue *et al*., 2000a, b; Yue *et al*., 2004; Danian *et al*, 1998; Chen *et al*., 2001, 2000; Atmadi *et al*., 2001; Rossmoore and Rossmoore, 1990; Sondossi *et al*., 2001). It was found that wet machining generates more fine airborne particles than dry machining (Sutherland *et al*., 2000; Zaghbani *et al*., 2008). Dry aerosols generated during metal machining processes have been found to be dependent on the workpiece material and its conditions as well as on the cutting parameters (Balout *et al*., 2007; Songmene *et al*., 2008a) and the tool geometry (Khettabi *et al*., 2007a, 2008b) employed. Recent experimental studies (Khettabi *et al*., 2007a, 2008b) show the important effect of different cutting parameters, tool geometry and workpiece material.

In this research, the mechanism of nano and micro particle emission during cutting metals is identified. The explanation of the origin of the particle emissions is based on phenomenological aspects: Energy approach combined with the friction and the plastic deformation of the workpiece material. The phenomenon is influenced by cutting parameters, material properties, temperature, shear stress, shear stress rate and force. The identification of the origin and the mechanisms of fine and ultrafine particle emission during machining can help to develop predictive models in order to locate the dangerous zones corresponding to the conditions under, which the dust emission is at a maximum.

ORIGIN OF PARTICLE EMISSION

The formation of fine particles during the cutting process can be caused by different phenomena: Thermal energy, plastic deformation, macroscopic and microscopic friction. The increase in temperature in the cutting zone helps to separate some particles. However, this process is expected to produce only very small (nano) particles. Because of the friction between micro-segments of the chip, the particles produced are micrometric and nanometric regarding their size. Similarly, the friction at the rake face produces different sizes of particles.

A predictive model developed by Khettabi *et al.* (2007a) was refined afterwards to include the properties of material, the cutting conditions and the tool geometry Khettabi *et al.* (2008b). The model is validated using results from experiments conducted on 6061-T6 aluminum alloy during dry and wet milling (Zaghbani *et al*., 2008) and on 6061-T6 aluminum alloy AISI 1018, AISI 4140

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steels and grey cast iron during an orthogonal turning process. Good agreement was found with experimental results (Khettabi *et al*., 2008).

$$D_u = A \times \frac{\beta_{max} - \beta}{\beta_c} \times R_a \times \eta_S \cdot \left(\frac{V_0}{V}\right)^{\delta} \exp\left(\frac{-E_A}{\tan\phi(1 - C_h \sin\alpha) V_c \frac{F_{sh}}{bf}}\right) \quad (1)$$

Where, D_u (dimensionless) is the dust unit defined as the dust mass divided by the chip mass. V (m min^{-1}) is the cutting speed, V_0 the cutting speed at, which the dust emission is maximum (Fig. 1), A is the factor of proportionality, δ is a material parameter introduced to characterize the ability of the material to produce metallic dust. For each material, a constant δ is attributed; β is a segmentation coefficient; η_S is the chip segmentation density; R_a is the roughness of the face of cut of the tool; E is the cutting energy; E_A is the activation energy of the particle; F_{sh} is the shear force; a is the rake angle and ϕ is the shear angle.

The Eq. 1 contains all important parameters: The energy, represented by the exponential term; the chip segmentation effect combined with roughness effect

$$\left[\frac{\beta_{max} - \beta}{\beta_c} \times R_a \times \eta_S\right],$$

the cutting speed combined with material effect (parameter δ). All these parameters influence the cutting process and the friction phenomenon, which causes the particles detachment during machining. Equation 1 is a semi-analytical equation developed using experimental data (Khettabi *et al*., 2007). This equation accounts for total particle emission due to friction, plastic deformation, shearing, chip deformation and bending, etc.

Micro friction: The machining process can be considered as cyclic (Astakhov *et al*., 2001). During chip formation, the deformation is located in thin shearing zone, producing a soft band. The slip in this zone during chip formation causes a friction in different forms. This microfriction is responsible for the fine and ultrafine particles generation, which is related to the cutting conditions, the material plasticity and the chip formation mode. An increase in the cutting speed is accompanied by an increase in the temperature in the primary and the secondary shear zones.

The effect of the cutting speed and the feed rate on particle emission is presented in Fig. 1a. An increase in the feed rate reduces the fraction of particle emitted per unit mass of chip removed (Fig. 1a). Therefore, for given mass of the chip, it is better to use higher feed rates than using low feed rates. This is also favorable for increasing the productivity. The effect of the cutting speed is characterized by a speed V° (about 200 m min^{-1} for the AISI 1018 steel) at, which the particle emission is maximal (Fig. 1a). This behavior was confirmed by previous studies (Balout *et al*., 2007; Khettabi *et al*., 2007a; Songmene *et al*., 2008b).

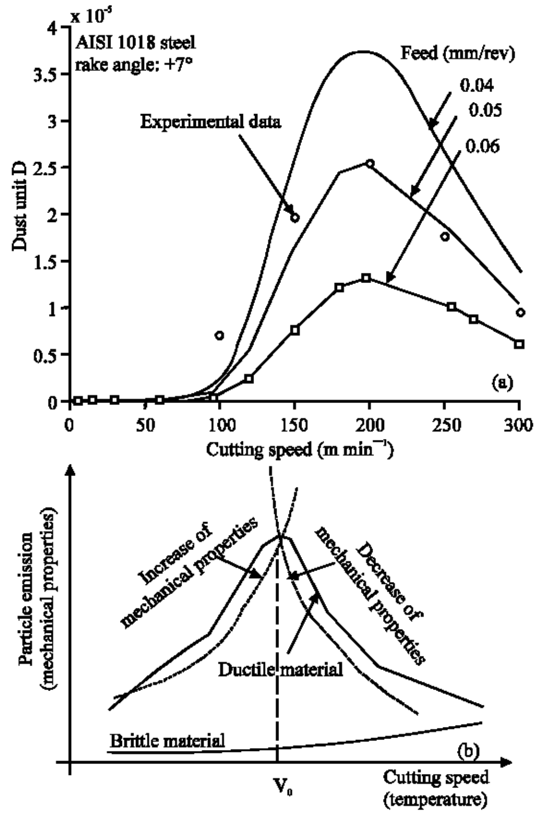

Fig. 1: Effect of cutting speed on mechanical behavior and Particle emission: a) Experimental and simulation results and b) Schematic behavior

The effect of the cutting speed is characterized by a competition of 2 phenomena (Fig. 1b): the friction in the chip shearing zone, which produces a lot of dust and the high ductile deformation, generalized in the mass of the chip. The friction produces particles only when the chip slip planes undergo a strong movement. Maximum dust generation is mainly due to this type of movement on the one hand and to the high density of the shearing planes, on the other. At very low speeds, the chip crack is controlled by its brittleness (Fig. 2-6). Because the crack opening; there is neither contact nor friction between its lips. At intermediate speeds, the slip planes are localized,

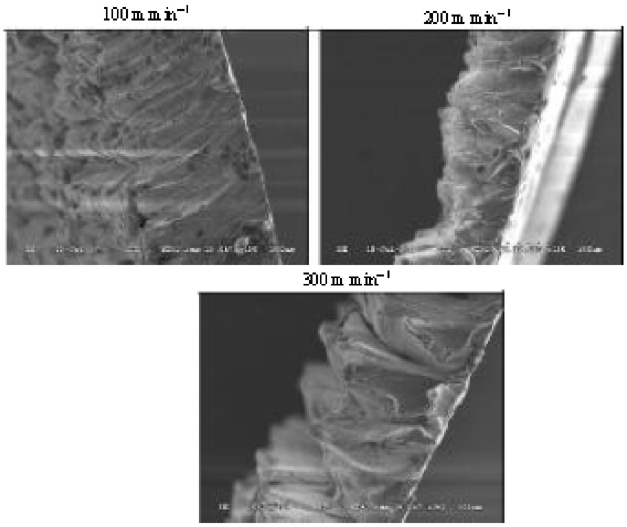

Fig. 2: Chip morphology of 6061-T6 as a function of cutting speed

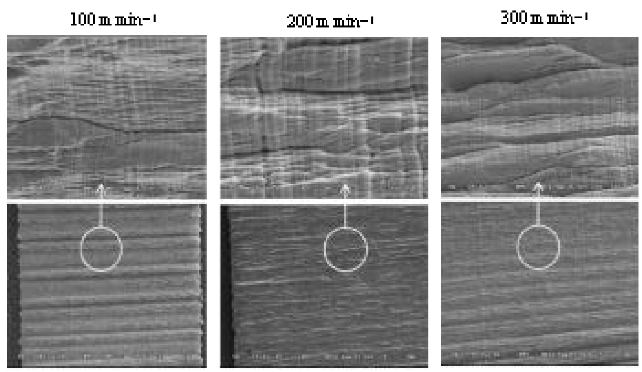

Fig. 3: External face of the chip of 6061-T6 as a function of cutting speed

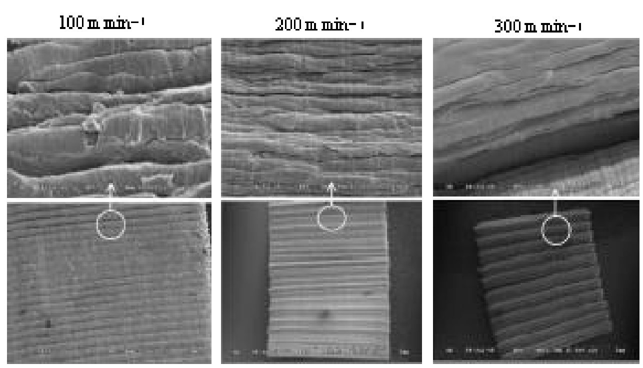

Fig. 4: External face of the chip of AISI 1018 as a function of cutting speed

their density increases, as the friction of the lips does. In this situation, the plastic deformation is limited and located in the shear plane (Fig. 2-6). Shear rates are therefore very important and help the particle detachment process. At high speeds, the density of segmentation is lower and the plastic deformation is delocalized; consequently, the generation of fine particle tends to decrease. If the lips of the crack open, which is the case with intrinsically fragile materials, there is no friction and thus the quantity of fine emitted particles is negligible.

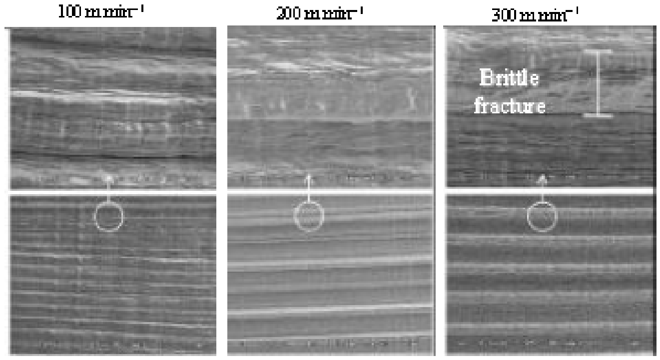

Fig. 5: External face of the chip of AISI 4140 as a function of cutting speed

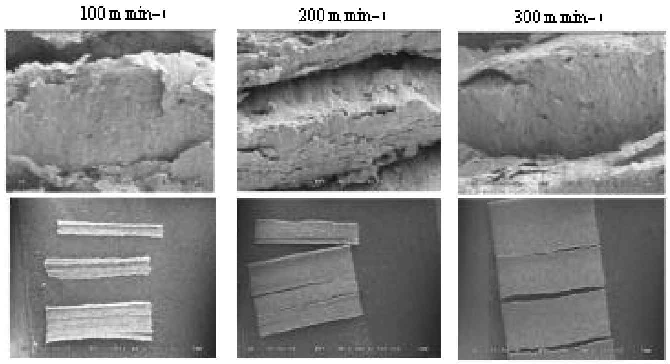

Fig. 6: External face of the chip of Grey cast iron as a function of cutting speed

Macro friction: Yang and Liu (2002) confirmed that the friction coefficients obtained in metal cutting represent a large difference with those of the same metal in conventional friction experiment. Furthermore, Shaw (2005) proposes a very representative friction model in machining, expressed in relationship between real area A, and the apparent area A. This ratio increases and approaches to 1 when the normal force increases.

$$\frac{A_r}{A} = 1 - e^{-BN} \qquad (2)$$

Where:

B = A constant for a material combination.
N = The applied load (normal force).

If the force applied increases (by increasing the cutting speed), the ratio becomes closer to the 1. However, the friction and the dust generation increase until they reach saturation. But, is it possible to admit that the increase of the real contact is due primarily and only to the normal force applied? Certainly not, because there is another phenomenon that can affects the force and the contact area, which is the temperature. The increase of temperature can soften the interfacial layers tool/chip, which increases consequently the real contact area.

The increase of the temperature in the shearing zone or at the tool tip results in an increase of the temperature at the tool-chip interface. According to Shaw (2005), the increase in the temperature due to the thermal energy of shearing in the primary shear zone can take the following form:

$$\Delta T = T_{sh} - T_0 = \frac{0.9}{1 + 1.329\sqrt{\frac{K_1 \gamma}{V_c f}}} \frac{\tau\gamma}{\rho C} \qquad (3)$$

Where:

T° = The room temperature.
T_{sh} = The shear temperature.
τ = The sear stress.
γ = The shear strain.
K_1 = The diffusivity.
V_c = The cutting speed.
ρC = The volume specific heat of the workpiece.
f = The feed rate.

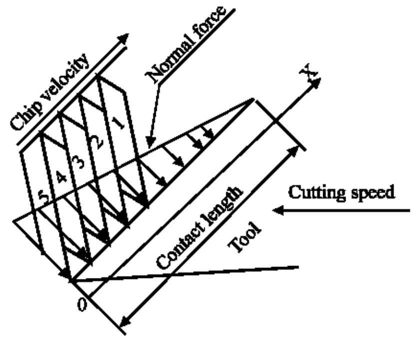

Fig. 7: Schematic representation of force distribution

It is more convenient to combine the two effects (load and temperature) in the same formula. Let us propose the following form:

$$\frac{A_r}{A} = 1 - (e^{-B_1 N} \times e^{-B_2 \Delta T}) \Leftrightarrow \frac{A_r}{A} = 1 - e^{-(B_1 N + B_2 \Delta T)} \quad (4)$$

where, B_1 and B_2 are constants.

With the load distribution at the interface proposed by Moufki *et al*. (2004).

$$N(X) = N_0 \left(1 - \frac{X}{l_C}\right)^{\xi} \quad (5)$$

where:

ξ = Parameter of load profile.
N_0 = The load at the tool tip.

Let us simplify calculations by admitting that the load distribution is linear as schematized in Fig. 7. Therefore,

$$N(X) = N_0 \left(1 - \frac{X}{l_C}\right) \quad (6)$$

Where, X isthe distance from the tool tip and parallel of the rake face. So, when X = l_C (contact length) the load becomes zero.

The particle emission due to friction, P_{fr}, can be estimated using the real area A_r.

$$P_{fr} = K \cdot A_r = K.A \cdot \left(1 - e^{-(B_1 N + B_2 \Delta T)}\right) \quad (7)$$

Where, K is a characteristic constant.

The dust quantity produced by this mechanism is also proportional to the segmentation frequency. The problem in this production zone is that friction also creates an increase in the temperature and the particles produced can be stocked on the chip surface. Those particles cause the abrasion of the part, thus producing more particles. The joining zones of the generated surface also produce particles, as hard as the parent materials.

Taking into account Eq. 6, the final equation of dust quantity produced by macrofriction becomes:

$$P_{fr} = K \cdot A_r = K \cdot A \cdot \left(1 - e^{-\left(B_1 N_0 \left(1 - \frac{X}{l_C}\right) + B_2 \Delta T\right)}\right) \quad (8)$$

According to the Eq. 8, the quantity produced by friction depends on the material properties, the load and the temperature affected by the cutting speed and the material properties (plasticity, density, heat transfer capability, etc.). It is quite difficult to isolate the micro or the macro friction in machining, but the Eq. 8 stills valid for both frictions (macro and micro). The load and the temperature are different in the interface tool-chip and slip planes, but the material parameters remain the same in different cutting zones. The Eq. 8 can be used to calculate the quantity of particle generated by friction in primary and secondary deformation zones, but one should remember that the shearing, the chip bending and the friction at the tool-workpiece interface and the tool wear also generate metallic particles.

Thermal energy: The energy given by the tool to the workpiece is transformed mostly to a thermal energy. Also, it can be enhanced by friction in different zones. The vibratory movement of the crystal lattice is the source of this energy. The crystal lattice of all materials at temperature of zero Kelvin is motionless. But as soon as the temperature starts to increase the lattice starts to vibrate with amplitudes and frequencies, which depend on the lattice thermal energy. If energy is sufficiently large, it will release the electrons in the first time then whole atoms, ions and nanoparticles. The thermal energy can produce only the small quantity of the nanoparticles.

MECHANISMS OF DUST EMISSION

Friction and stacking fault energy: Chip formation can effectively be an indicator of some dust emission mechanisms. Figure 8 illustrates the mechanism of dust emission by friction of the chip against the tool rake face. Particle formation by friction goes through 2 main steps, depending on the workpiece material: Step 1 occurs during the material separation while, Step 2 takes place when the chip slides against the tool rake face. In the case

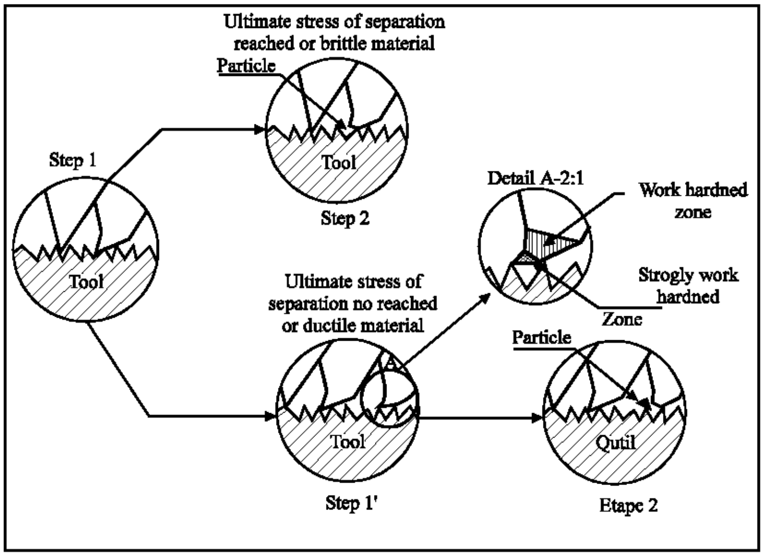

Fig. 8: Mechanism of particle detachment

of brittle materials, the chip is formed by brittle fracture, with the chip contact length being very small. In that situation, the contact between the tool material and the irregular chip surface can break up particles from the internal chip surface. If the workpiece material is ductile, the chip will be formed by micro-segments that undergo a local work hardening due to the action of some asperities of the tool rake face. Then, the hardened small part is separated by a local brittle fracture. This mechanism describes how friction or microfriction can produce small particles during machining. The size of the particles separated depends on the tool rake face roughness, the cutting conditions and the workpiece material.

The stacking fault energy is an important parameter to characterize the material plasticity (Fujita *et al.*, 2007). During the deformation, the interaction mechanisms between dislocation and grain boundary must depend closely on the Stacking Fault Energy (SFE). When the SFE is low, the size of the grains after deformation is small and consequently, it is expected that the particles produced during machining of materials with small SFE be smaller than a material with more important stacking fault energy. Alloying elements affect significantly the grain size and SFE (Li *et al.*, 1999). Some elements like (Mn, Cr and Ni) can amplify the SFE in the case of iron based shape memory alloys, while Si has the opposite effect on SFE (Li *et al.*, 1999). With a different treatment, such as heat treatment, it should be possible to change the grain size in order to optimize the particle emissions during machining. In a long term, a classification of materials according to their capability to generate metallic dust during shaping or cutting could help manufacturers to select materials or to adjust cutting data. Such a classification could be based on main material properties, such as Stacking Fault Energy (SFE). However, it is a most to first develop a testing and classification standard for fine and ultrafine metallic particle emission.

CONCLUSION

The generation of micronic and submicronic particles during machining depends on workpiece material, cutting parameters and tool geometry. Understanding particle emission mechanisms can allow developing a predictive model and strategies to limit metallic dust emission at the source. Micronic and submicronic particle emission during cutting process is a complex phenomenon:

- The formation of fine particles during the cutting process can be caused by different phenomena: Thermal energy, plastic deformation, macroscopic and microscopic friction.
- The effect of the cutting speed is characterized by a competition of two phenomena: The friction in the chip shearing zone, which produces a lot of dust and a high ductile deformation, generalized in the mass of the chip.
- The main phenomenon of particles generated during machining is the friction, which is dictated by the material plasticity in the different level: Macroscopic at the interface tool/chip and microscopic in the primary shear zone.

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