Proceedings of 1st International Conference on Aeronautics Sciences. ICAS. 2013

Dust Emission During Dry Machining of Aeronautic Aluminum Alloys

A. Djebara*, W. Jomaa, A. Bahloul*, V. Songmene****

** Institut Robert-Sauvé en Santé et sécurité du travail, IRSST, 505 boul. De Maisonneuve West, Montréal (Qc) H3A 3C2, Canada, E-mail: Abdelhakim.Djebara@irsst.qc.ca, Ali.Bahloul@irsst.qc.ca*
*** Department of mechanical Engineering, École de Technologie Supérieure, ÉTS, 1100 Notre-Dame West, Montréal (Qc) H3C 1K3, Canada, E-mail: Walid.Jomaa.1@ens.etsmtl.ca, Victor.Songmene@etsmtl.ca*

Abstract

The manufacturing of aeronautical components requires accuracy, repeatability and efficiency. Nevertheless, for today industry, machining processes should not only be effective in terms of technical requirements and economic issues, but also they should be sustainable in terms of environments and operator's safety. It is well known that the use of cutting fluids during machining is costly and can be hazardous for the operator. However, the dry machining induces excessive friction on the tool/workpiece and chip/cutting tool interfaces leading to increased emission of fine particles and nanoparticles which deteriorate the workshop air quality, can constitute a real risk to the health of operators and shorten the reliability of the machine-tools components. Knowing the conditions leading to reduced metallic particle emission could help improving the occupational safety of the machining processes. This paper presents experimental and theoretical investigations on particle emission phenomenon during dry machining of aluminum alloys (7075-T6 and 6061-T6) used in aeronautic applications. The main goal is to predict the particle emission as a function of machining conditions in order to determine safe and economic machining process windows.

KEY WORDS: *Aluminum alloys, dry machining, dust emission, air quality, cutting energy.*

1. Introduction

The performance of modern metalworking processes is not limited to standard criteria such as productivity, precision, surface quality or cycle time anymore. The potential health hazards associated with the machining has become another machining process performance indicator to consider [1]. Generally, all machining processes generate aerosols in solid or liquid forms. In the air, both aerosols forms can be inhaled and therefore threaten human health. Solid aerosols are generated from workpiece material during dry and wet machining, while liquid aerosol production is caused by the use of cutting fluids [2, 3]. The primary mechanisms responsible for wet aerosol production include fluid impact on the workpiece and also evaporation [4, 5, 6 & 7]. Cutting fluids are not only toxic [8, 9], but are also costly (initial purchase and treatment of used fluids). The emission of liquid aerosols caused by cutting fluids can be eliminated by using dry machining. However, the problem of the solid aerosols still remains in this case [10]. Most of the dust generated in dry machining can be fine or ultrafine and it is considered respirable. Further, the accumulation of any dust in a manufacturing facility can be problematic from the regulatory perspective. In fact, dust and debris has been blamed to prevent part contamination or damage in manufacturing facilities. Many governments to more closely monitor and regulate dust accumulation in all manufacturing environments [11]. Advanced aluminum materials are providing remarkable opportunities for weight reduction versus structural strength in the new generation of aircraft. Previous research showed that machining of aluminum alloys is usually accompanied by fine and ultrafine conductive and abrasive dust emission [12]. Hence, there is a need to provide a variety of solutions to alleviate these concerns by ensuring the operator safety and protection for the machine tool and surrounding equipment to prevent aluminum dust entering electronic and mechanical parts.

The characterization and measurement of dust emission require advanced equipment and time consuming tests especially when new materials grade are concerned. Thereby, predictive modeling of dust emissions is required. The literature contains limited models for the prediction of dust emissions during machining processes, and most are not applicable to metals [13, 14]. For the metallic dust emission during machining processes, the following process parameters were found important [15]: cutting conditions (cutting speed, depth of cut and feed rate), tool geometry (rake angle, and lead angle) and workpiece material. These parameters influence the shearing of metal, the friction and the plastic deformation. Friction can thus cause particle detachment by various means. Ko et al. (2001) shows the effect of the surface roughness on particle emission [16]. Akarca et al. (2005) found that during sliding wear of the 356 aluminum alloy, wear particles are generated by the nucleation of voids and the propagation of micro-cracks at a certain depth under the surface [17]. Rautio et al. (2007) developed an empirical model for dust emission. They found that the fraction of dust mass generated to the chip removed from the workpiece material is inversely proportional to the chip thickness [18]. They then concluded that the fraction of dust generated is proportional to the ratio of the cutting speed to the feed rate used. This model is simple and very convenient, but was validated only on medium-density fiberboard materials.

In the current paper, the effects of cutting speed and cutting feed on dust emission during machining of aeronautical aluminum alloys (6061-T6 and 7075-T6) were studied. Relationship among chip morphology, specific energies (shearing and friction) and dust emission were established. A dust emission model [15] taking into account the machining conditions and a work material property was validated through experimental results.

2. Testing Procedures

Dry and orthogonal machining tests were conducted on a three-axis MAZAK CNC machine-tool (12 000 rpm) using ISO TNMA160408 uncoated carbide insert (K68 grade from Kennametal) . A shaped disk workpiece with a diameter of 70 mm and a width of 4.3 mm were used in the experiment. A laser photometer (TSI8520 DusTrack^{TM}) was used to quantify the particles produced. The DusTrack^{TM} was connected to limps of collection by a suction pipe at a flow rate of 1.5 l/min from the cutting area (or near this area). The dust sampling was carried out before, during and after each cutting process to return to initial ambient concentration. Cutting forces were measured using a three-axis table dynamometer (Kistler 9255-B) on the machine table. A computer equipped with a data acquisition and analysis system was also connected to the measuring device. Scanning Electronic Microscope (SEM) was used to examine the chips under different conditions. The experimental setup is shown in Fig. 1.

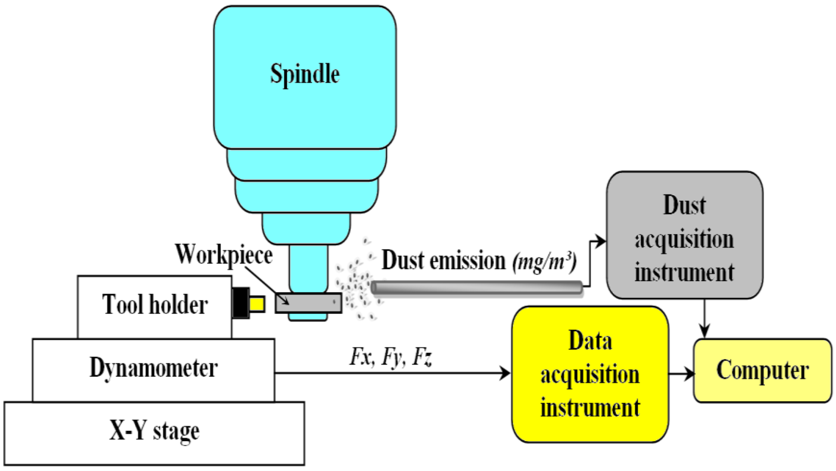


Fig. 1 Experimental setup: Orthogonal cutting

In order to be efficient and to reduce the costly full factorial machining tests, a central composite design with 5 levels of speeds and 5 levels of feeds was used in the design of experiments for this investigation. The cutting speed used ranged from 150 to 1200 m/min and the cutting feed was ranged from 0.01 to 0.3 mm/rev. The total mass concentration of dust emission representing the total mass per unit volume was computed from the particle number concentration and used as one output response. The total number of experiments performed was 12 experiments.

3. Results and Discussion

3.1. Dust emission

Observations on scanning electron microscope showed the particles to be heterogeneous and agglomerated (Fig. 2). This morphology depends on the nature of the material and the mechanism that produced it. Similarly, the agglomeration of particles did not lead to spherical particles.

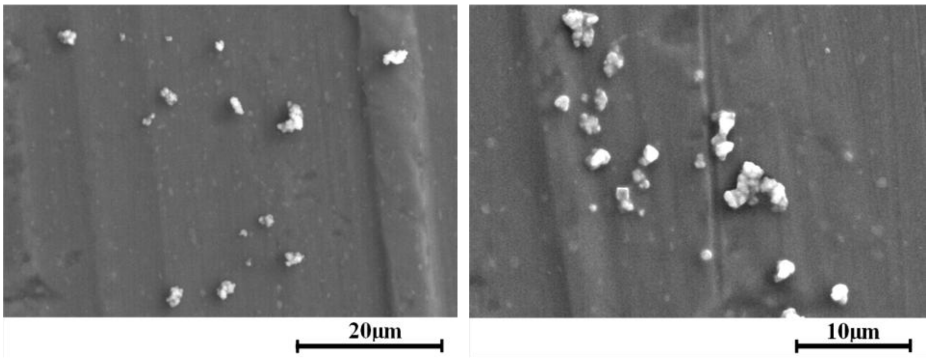


Fig. 2 SEM image of particles emitted during machining of A6061-T6 alloy

For this investigation (Fig. 2), a dust predictive model for dust emissions develped by [15] was used. The model is based on chip segmentation, tool rake face roughness, cutting parameters, workpiece material and particle detachment energy. The main advantage of this model is to predict the dust emission based on cutting data, materials properties and tool geometry. The predictive model is given as follow [15] :

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

Where A is the factor of proportionality and 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. The parameter δ is experimentally determined to obey the following criteria (Eq. 2).

$$\delta \equiv \begin{cases} \delta \geq 1 \rightarrow \; Ductile\ \ materials \\ 0.5 < \delta < 1 \rightarrow \; semi-ductile\ \ materials \\ 0 < \delta \leq 0.5 \rightarrow Britlle\ \ materials \end{cases} \tag{2}$$

All parameters in Eq. 1, such as the rake angle α, the shear angle ϕ, the cutting speed V, the feed f, the tool roughness R_a, The chip segmentation density η_S, the maximum value of chip segmentation coefficient β_{max}, and the critical value for which the chip becomes segmented β_c, can be known or easily determined. The shearing force and temperature can be estimated with using the Needelman-Lemonds constitutive equations.

Fig. 3 and Fig.4 present the experimental data and the simulation results for dust emission as a function of the feeds and cutting speeds for dry machining of aluminum alloy 6061-T6 and 7075-T6. The experimental results show that the emission of dust during machining decreases significantly with cutting speed during machining of both tested alloys. At low speeds, the dust emission is maximal and comparable for two materials tested. The 7075-T6 aluminum alloy can however emit more than the 6061-T6 aluminum alloy in the same cutting conditions. On the other side, the increase in the feed rate reduces the amount of dust generated during machining.

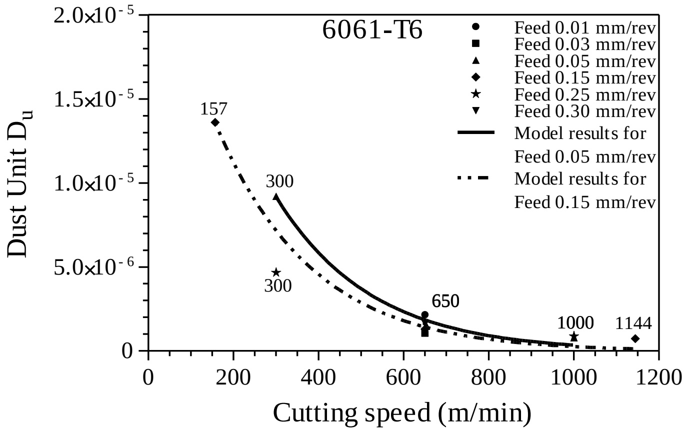


Fig. 3 Effect of cutting speed and cutting feed on dust emission during machining of 061-T6 aluminum alloy

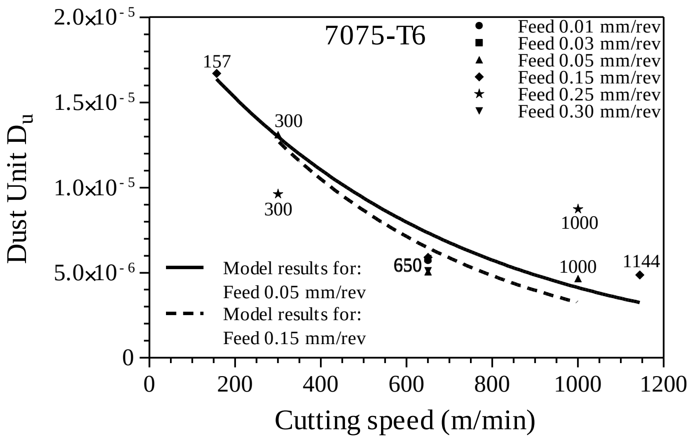


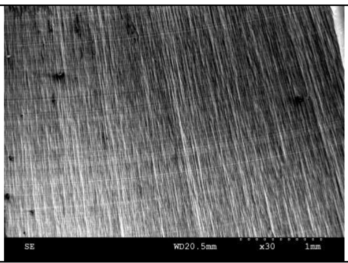
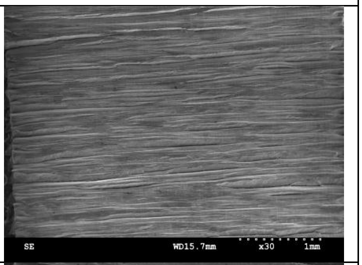
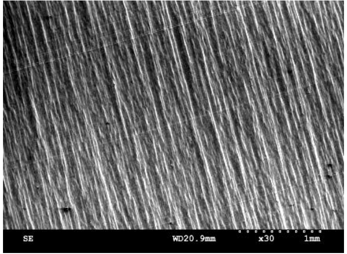
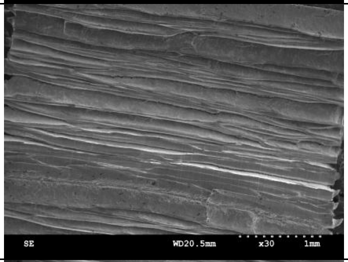
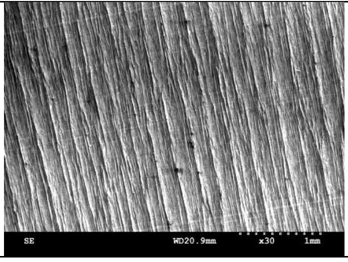
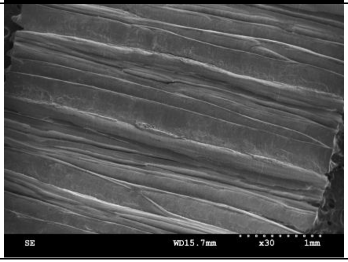
Fig. 4 Effect of cutting speed and cutting feed on dust emission during machining of 7075-T6 aluminum alloy

3.2. Chip Morphology Analysis

The chip morphology was analyzed in this study using SEM microscope. Table 1 shows the different chip morphologies obtained during machining of 6061-T6 and 7075-T6 aluminum alloys at different cutting speeds. The chip patterns produced are similar and they are dense and strongly crushed against one another for low speed which corresponds to the maximum production of dust (Fig. 3 and Fig. 4). The shear bands are more spaced for cutting conditions generating less dust (high cutting speeds). The chip morphology can give an indication of the deformation that took place during the process, and explains some of the variability in dust emissions. Chip morphology due to the flow of material of the workpiece according to cutting conditions, forms bands of different sizes (Table 1). The chip formation is influenced not only by the cutting speed, but also by the workpiece material which may explain the difference on dust emission for the tested aluminum alloys in the given cutting conditions.

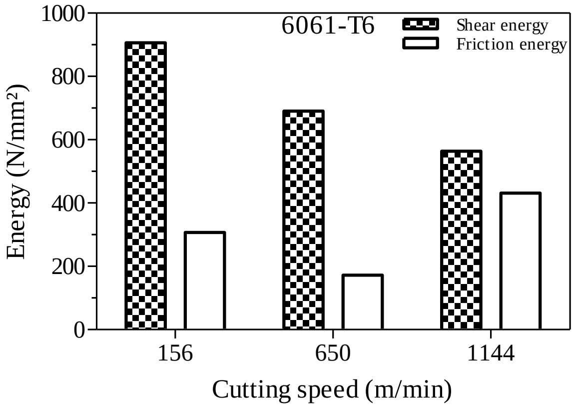
Table 1

Chip formation during machining of 6061-T6 and 7075-T6 aluminum alloys at different cutting speed for a feed rate of 0.15 mm/rev

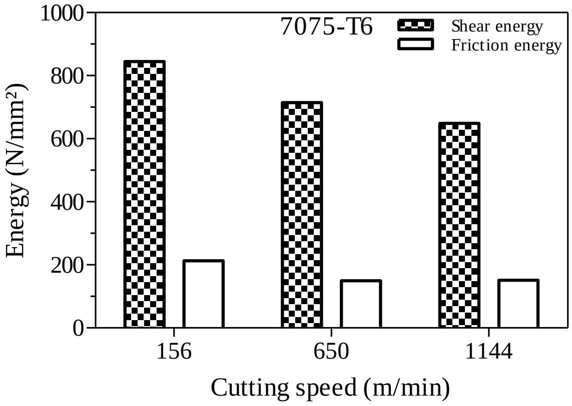
Cutting speed (m/min)	Workpiece materials	
	6061-T6	7075-T6
157		
650		
1144		

3.3. Cutting Energy

Fig. 5 shows the trend of the cutting energy during machining of 6061-T6 and 7075-T6 aluminum alloys. Specific shearing and friction energies were calculated based on the measured cutting forces and chip compression ratios. The specific cutting energy is defined as the sum of the specific shear and friction energies. As expected, the friction energy is smaller compared to the shearing energy for each test. One can see that the shearing energy decreases as the cutting speed increases. Besides, accentuated friction is observed during machining of 6061-T6 alloy compared to 7075-T6 alloy. This is clearly shown by the effect of cutting speed on chip/tool contact length in Fig. 6. An increase in the cutting speed is accompanied by an increase in the friction energy in the case of 6061-T6, but in the case of 7075-T6, the friction energy is constant for each test. These results leads the majority of the quantity of emitted particles is through the shearing zone and explains the greater emissivity of 7075-T6 relative to 6061-T6 aluminum alloys (Fig. 3, Fig. 4 and Fig. 5).



(a)



(b)

Fig. 5 Effect of cutting speed on cutting energy during machining of 6061-T6 and 7075-T6 aluminum alloys

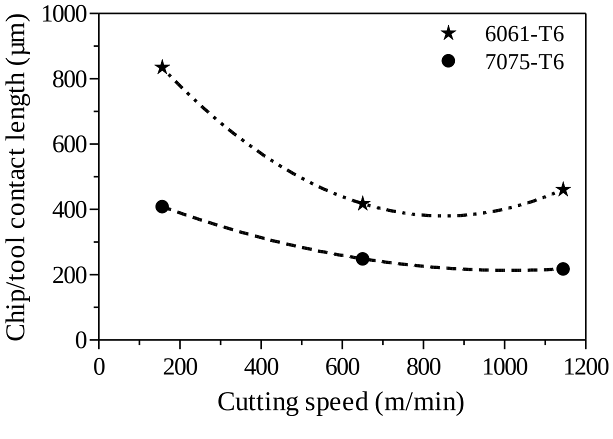


Fig. 6 Effect of cutting speed on chip/tool contact length

3.4. Discussion

After examination of the chips morphology, it was observed that, in general, a lot of particles were broken in the chips when cutting at low speeds. Fig. 7 shows an example of particles located between two shear bands in a chip at low speed. At very low speeds, the slip planes are localized, their density increases as does the friction of the lips (Table 1). In this situation, the plastic deformation is limited and located in the shear plane. Shear rates are therefore considered very important, and help in the particle detachment process. At very high speeds, the density of segmentation is lower, and the plastic deformation is delocalized; consequently, the dust generation tends to decrease. If the lips of the crack open, which is the case with 7075-T6 aluminum alloy, there is no friction in the chip shearing zone. By cons, the majority of the quantity of emitted particles is through the friction zone tool/chip. Dust generation is also a phenomenon related to 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 is characterized by a competition of two phenomena: the friction in the chip shearing zone, which produces a lot of dust, and the high ductile deformation, spread with the chip mass. The friction produces particles only when the chip slip planes undergo a strong movement. Maximum dust generation is mainly due to the high density of the shearing planes on the one hand, and to the friction zone tool/chip, on the other.

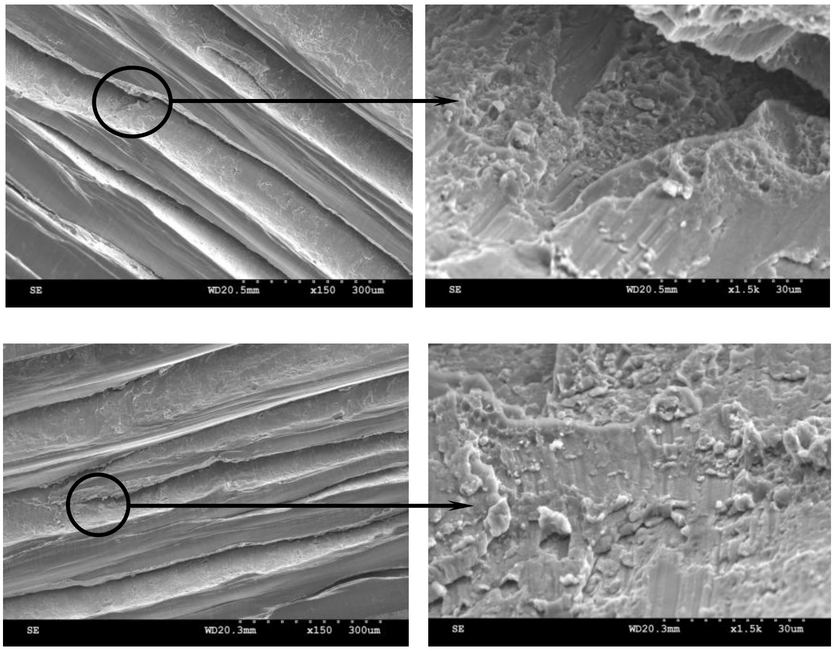


Fig. 7 Shearing zone which produces dust at the cutting speed of 300 m/min and feed rate of 0.15 mm/rev for dry machining of aluminum alloy 7075-T6

4. Conclusions

It has been proved that the cutting conditions influence significantly the dust generation. The experiment and simulation results show that the cutting speed is determinant for dust emission as compared to the effect of the feed rate and the workpiece materials. An increase in the cutting speed and feed rate also reduces dust emissions because the chip becomes segmented. This examination indicates that it is possible to machine parts at very high speeds, which ensures high productivity, good parts quality, and without producing harmful dust. For the 7075-T6 aluminum alloy, the influence of the friction energy on dust emissions during cutting is constant for each test. However, in the case of the 6061-T6 aluminum alloy, the influence of the friction energy on dust emissions is much higher than in the case of the 7075-T6 aluminum alloy. By comparing the results obtained for the two types of aluminum alloys, the influence of the shearing energy on dust emission is most significant. The results obtained make clear that the majority of the quantity of emitted particles is through the shearing zone. It is also observed that the order is not respected with regards to the friction energy because there is no complete proportionality between the friction energy and the dust quantity, but there is a sum of the specific shear and friction energies in which production reaches its maximum.

References

1. **Chan, T. L., D'Arcy, J. B., & Siak, J**. Size characteristics of machining fluid aerosols in an industrial metalworking environment. Applied Occupational and Environmental Hygiene, 1990, vol. 5, no 3, p. 162-170.
2. **Yue, Y., Gunter, K. L., Michalek, D. J., et al**. Cutting Fluid Mist Formation in Turning via Atomization Part 1: Model Development. IMECE Proc. of ASME: Manufacturing Engineering Division, 2000, p. 843-850.
3. **Yue, Y., Sun, J., Gunter, K. L., et al**. Character and behavior of mist generated by application of cutting fluid to a rotating cylindrical workpiece, Part 1: model development. Transactions-American Society of Mechanical Engineers Journal of Manufacturing Science and Engineering, 2004, vol. 126, p. 417-425.
4. **Chen, Z. Liang, S.Y., & Yamaguchi, H**. Predictive Modeling of Cutting Fluid Aerosol Generation in Cylindrical Grinding, NAMRC, May 21-24-2002 (West Lafayette, ID). Society of Manufacturing Engineers, p. 1-8.
5. **Atmadi, Alexander, Stephenson, A., & Liang, S. Y**. Cutting fluid aerosol from splash in turning: analysis for environmentally conscious machining. The International Journal of Advanced Manufacturing Technology, 2001, vol. 17, no 4, p. 238-243.
6. **Bell, D. D., Chou, J., Nowag, L., & Liang, S. Y**. Modeling of the Environmental Effect of Cutting Fluid. Tribology transactions, 1999, vol. 42, no 1, p. 168-173.
7. **Chen, D., Sarumi, M., & Al-Hassani, S. T. S**. Computational mean particle erosion model. Wear, 1998, vol. 214, no 1, p. 64-73.
8. **Rossmoore H.W., & Rossmoore, L.A**. Effect of Microbial Growth Products on Biocide Activity in Metalworking Fluids, Symposium on Extra cellular Microbial Products in Bio-Deterioration, vol. 27, no 2, Apr 9–10, 1990, International Bio-deterioration, 1990, p 145–156
9. **Sondossi, M., Rossmoore H.W. et al**. Relative Formaldehyde Resistance among Bacterial Survivors of Biocide-Treated Metalworking Fluid, Int. Biodeter. Biodegr., 2001, vol. 48, no 1–4, p 286–300
10. **Sutherland J.W., V.N. Kulur, and N.C. King**. Experimental Investigation of Air Quality in Wet and Dry Turning. CIRP Ann. Manuf. Technol., 2000, vol. 49, no 1, p 61–64.
11. **Dhar N.R. & M.W. Islam**. The Influence of Minimum Quantity of Lubrication (MQL) on Cutting Temperature, Chip and Dimensional Accuracy in Turning AISI-1040 Steel. J. Mater. Process. Technol., 2006, vol. 171, no 1, p 93–99.
12. **Djebara A., V. Songmene, R. Khettabi, J. Kouam**. An Experimental Investigation on Ultrafine Particles Emission during Milling Process Using Statistical Analysis. International Journal of Advances in Machining and Forming Operations, 2012, vol. 4 No.1 pp. 15-37.
13. **Steven, J. P., & John A**. **O**. Semi-Empirical model for predicting surface coal mine drill respirable dust emission. Int. J. of Surface Mining, Reclamation and Environment. 2004, vol. 18, no 1, p. 42-59.
14. **Zipf, J.R.K., Bieniawski, Z.T**. A fundamental study of respirable dust generation in coal. Min. Sci. Technol. 1989, vol. 9, no 1, p. 87–99.
15. **Khettabi, R., Songmene, V**. Modeling of Particle Emission during Dry Orthogonal Cutting. Journal of Materials Engineering and Performance. 2010, vol. 19, no 6, p. 776-789.
16. **Ko, P. L., Iyer, S. S, Vaughan, H., Gadala, M**. Finite element modeling of crack growth and wear particle formation in sliding contact. Wear, 2001, vol. 250-251, p. 1265-1278.
17. **Akarca, Altenhof, S. S, W. Alpas, J., A.T**. Characterization and modeling of subsurface damage in a 356 aluminum alloy subjected to multiple asperity sliding contacts, Minerals, Metals and Materials Society, Warrendale, PA 15086, United States, 2005, p. 107-120.
18. **Rautio S., P. Hynynen, I. Welling, I. Hemmil, P. Usenius & A. Narhi**. Modeling of airborne dust emissions in CNC MDF milling. Holz als Roh- und Werkstoff, 2007, vol. 65, no 7, p. 335-341.