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Analytical Model to predict Sauter Mean Diameter in Air Assisted Atomizers for MQL in Machining Application

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Abstract

The threat posed by coolants to environment and worker health, escalating manufacturing costs due to coolant usage and stringent regulations enforced by the government for coolant waste disposal trigger research in unconventional coolant delivery techniques. Minimum Quantity Lubrication (MQL) is a technique delivering very small amount of coolant in the form of spray droplets that easily penetrate the tool-work piece interface for improving the cutting action, augmenting tool life and work piece quality. The droplet size which plays an import role in removing the heat and provide a lubrication action in the contact zone is controlled by the spray parameters. In this paper, an analytical model has been developed to determine the Sauter Mean Diameter (SMD) of coolant spray in MQL applied to machining processes, as a function of the spray parameters such as air pressure, viscosity of air, coolant flow rate, surface tension and density of coolant oil, based on the first principles and the conservation methods. The model developed has been validated with the experimental results and it has correlated well with reasonable accuracy.

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*Keywords:*Minimum Quantity Lubrication;Sauter Mean Diameter;Analytical Model

1. Introduction

In the recent past, a lot of global summits are held to make policies on mitigation of environmental degradation in the light of expediting technology. The legislators of the developed countries are highly focused to cut down the industrial pollution and warrant environment friendly processes. So, the industrial coolant disposal which causes severe negative effects to the environment has been subjected to stringent laws and regulations and hence the cost of disposal is rapidly rising. Moreover, coolants account for a large portion of the machining costs. The aforementioned reasons have triggered research in alternate fluid delivery techniques such as Dry Machining and Minimum Quantity Lubrication.[1]

Dry machining involves the complete elimination of the coolant from the machining process. The main purpose of the coolant is to lubricate the work-tool interface and to effectively transfer heat produced by friction. Thus the absence of coolant results in escalating temperatures, poor finish of the machined surface. It also drastically reduces the tool life and work piece quality. Thus, Minimum Quantity Lubrication (MQL) using very small amounts of coolant serves as a better option as it does not compromise on the results and at the same time reduces coolant usage. The droplets have a much greater surface area than the solid jets in the currently employed conventional flood cooling. The greater surface area assures better heat transfer rate. In the case of lubrication, the smaller droplets easily penetrate the work-tool interface than the conventional jets.[2,3,4,5]

The main parameters that decide the performance of MQL in machining are the droplet size and its distribution. In MQL air assisted atomization of the coolant is carried out to produce droplets. The coolant with a very low flow rate is impinged co axially by pressurized air that expands to a very high velocity in the co axial nozzle. Consequently the coolant

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film breaks up into ligaments and then fine droplets. The droplets deposit and wet the tool-work interface lubricating the process and removing the heat. The diameter of the droplet determines the wetting area controlling the lubrication and the surface area controlling the heat transfer rate. However, the droplet diameter in turn is dependent on the spray parameters and the properties of coolant oil.

Kyung et al. [6] developed a new technique to measure the droplet sizes in a typical MQL process and their distribution after the droplets have been sprayed onto the polished silicon wafer surface. Three-dimensional (3D) surface characterization of the droplet surface has been obtained from Confocal Laser Scanning Microscopy (CLSM) for the droplet volume measurement. Edge detection algorithm (EDA) has been used to obtain the droplet distribution in terms of nozzle distances and air pressures, to study the effects of air pressure on the droplet size and distribution.

T.Tawakoli et al. [7] studied the effect of oil mist parameters on surface roughness and tangential cutting forces in grinding with MQL application. The effects of nozzle position, mist deposition distance and the effects of air pressure and MQL flow rate on wetting area were studied.

M.Emami et al.[8] studied the liquid atomization characteristics of an air-assisted atomizing nozzle including carrier gas velocity, liquid mean droplet size and droplet velocity profiles to determine the appropriate range for spray parameters for MQL grinding of Al_2O_3 ceramics.

A.S.S.Balan et al. [9], simulated the atomization of oil mist using CFD model to determine the optimal air pressure and coolant flow rate for obtaining best results in MQL Grinding of Inconel 751 super alloy and validated it with experiments.

T.-W.Lee et al. [10] developed an alternative method for calculating drop size distributions in atomized sprays by solving the integral form of conservation equations of mass, momentum and energy with iterative methods.

The study on literature shows the lack of an analytical model to relate the droplet diameter and the input spray parameters in air-assisted atomizers for MQL application in machining. In this paper, an analytical model is developed to determine the Sauter Mean Diameter of droplets in air-assisted atomizers for MQL applications, as a function of the spray parameters such as the air pressure, viscosity of air, coolant flow rate, surface tension and density of coolant oil based on the integral form of the conservation equations of mass, momentum and energy.

2. Body

2.1 Methodology

Based on the conditions and the properties of the fluid and the air, the analytical model is developed to predict the Sauter Mean Diameter of the air atomized spray system. In order to reduce the complexity of the model, the following assumptions were made and based on these the analytical model is formulated.

- There is no heat and mass transfer and hence the temperature of both oil and air remain constant.
- Turbulence is not taken into account in the model.
- Gravitational effects are neglected.
- Air is assumed to be continuous fluid and oil is assumed to be a discrete phase owing to the fact that volume fraction of oil in air is very low.
- Droplets of oil are assumed to be perfectly spherical.
- Oil is considered to be incompressible.
- The swirl component of both the gas and the liquid velocities is neglected as the atomizer considered for the model.
- The effect of ambient air is neglected to reduce the complexity of the model.
- Liquid will deform under aerodynamic loading and that droplets have tendency to form groups, but the empirical drag coefficient for single solid sphere is commonly assumed.
- Secondary atomization is not considered.
- Droplet Interactions are not considered.

The schematic of the air assisted atomizer is shown in Fig 1. It shows the coolant with very low flow rate being surrounded co-axially by pressurized air which upon expansion through the nozzle impinges the solid jet with high velocity, breaking it into droplets.

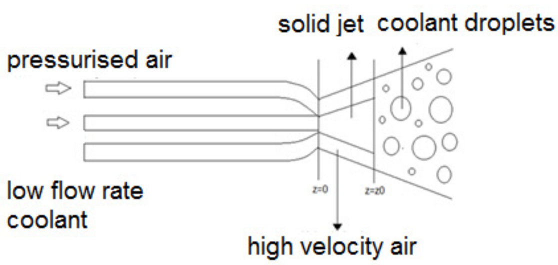

Fig. 1. Schematic of air assisted atomizer

The conservation of mass results in an expression for the number of droplets per unit volume. The number of droplets per unit volume can be formulated from the mass continuity equation as in (1): [10]

$$d_v = \frac{Q_c}{\frac{\pi}{6} u_z \int_0^R \int_0^\infty D^3 \frac{dN}{dD} 2\pi r D D dr} \quad (1)$$

The droplet size distribution can be represented as a histogram of droplet number increment $\Delta N / \Delta D$, plotted vs.

droplet size D . [11] The number of droplets per unit volume derived from the conservation of mass is made use in the derivation of energy terms. According to the law of conservation of energy, the kinetic energy of the high velocity air is consumed to break the liquid into smaller droplets (surface energy) and to drag the low velocity coolant droplets. As quoted by T.-W.Lee et al. [10], the viscous dissipation is also accounted. Thus the conservation of energy can be written as in (2):

$$\Delta \dot{KE}_a = \dot{W}_d + \dot{S} + \dot{V} \quad (2)$$

The change in kinetic energy of air can be expressed as in (3):

$$\Delta \dot{KE}_a = \frac{1}{2}\rho_a Q_a \left(v_i^2 - v^2\right) \quad (3)$$

The total surface energy rate is given as in (4):

$$\dot{S} = \int_0^R \int_0^\infty d_v \sigma\pi D^2 u_z \frac{dN}{dD} 2\pi R dD dr \quad (4)$$

Sauter Mean Diameter (SMD) is a measure of the fineness of a spray in terms. SMD is the diameter of a drop having the same volume to surface area ratio as that of the total volume of all the drops to the total surface area of all the drops. [13].It can be expressed as in (5):

$$D' = \frac{\int_0^\infty D^3 \frac{dN}{dD} dD}{\int_0^\infty D^2 \frac{dN}{dD} dD} \quad (5)$$

Substituting for the number of droplets per unit volume from (1) and simplifying for D', (4) becomes,

$$\dot{S} = Q_c \frac{6\sigma}{D'} \quad (6)$$

Having derived the equations for change in kinetic energy and surface energy, an equation for drag work is attempted. The rate of work done due to drag force exerted by faster moving air on the droplets is in(7):

$$\dot{W}_d = \int_{Z_0}^{Z} \int_0^R \int_0^\infty d_v F_D w_r \frac{dN}{dD} 2\pi R dD dr dz \quad (7)$$

The relative velocity, drag force in an individual direction and the total drag force are given in (8), (9) and (10)

$$w_r = \sqrt{\left(v_z - u_z\right)^2 + \left(v_r - u_r\right)^2} \quad (8)$$

$$F_{D_i} = \frac{1}{2}\rho_a w_r \left(v_i - u_i\right) C_D \frac{\pi}{4} D^2 \quad (9)$$

$$F_D = F_{D_z} + F_{D_r} \quad (10)$$

The coefficient of drag is referred from [14] and neglecting higher order terms, is in (11)

$$C_D = \frac{24}{Re}\left[1 + \frac{1}{6} Re^{\frac{2}{3}}\right] \quad (11)$$

Reynolds Number for the droplet is given in (12)

$$Re = \frac{w_r D'}{\vartheta_a} \quad (12)$$

On substitution of (8),(9) and (10) in (7) and simplifying, the rate of drag work becomes,

$$\dot{W}_d = \frac{3}{4}\rho_a \int_{Z_0}^{Z} \frac{Q_c}{D'} \frac{C_D}{u_z} w_r^2 \left[\left(v_z - u_z\right) + \left(v_r - u_r\right)\right] dz \quad (13)$$

The viscosity of air, dissipates the velocity of air and thereby its kinetic energy. The dissipated energy can be written as in (14) [10, 12]

$$\dot{V} = 6X\mu_a \int_{z_0}^{z} \frac{Q_c w_r^2 \sqrt{Re}}{u_z \left(D'\right)^2} dz \;; X=3.5 \quad (14)$$

On substituting (3), (6), (13) and (14) in the energy equation (2) and simplifying, the mathematical model for Sauter Mean Diameter (D') is obtained as in (15)

$$D' = \frac{Q_c 6\sigma}{\frac{1}{2}\rho_a Q_a \left(v_i^2 - v^2\right)} + \frac{3Q_c C_D}{2Q_a \left(v_i^2 - v^2\right)} \int_{Z_0}^{Z} \frac{w_r^2 \left[\left(v_z - u_z\right) + \left(v_r - u_r\right)\right]}{u_z} dz + \frac{12X\mu_a}{\rho_a Q_a \left(v_i^2 - v^2\right)} \int_{Z_0}^{Z} \frac{Q_c w_r^{\left(\frac{5}{2}\right)}}{u_z D'^{\left(\frac{1}{2}\right)} \vartheta_g^{\left(\frac{1}{2}\right)}} dz \quad (15)$$

To determine the velocity profile that can be substituted in the model for calculating Sauter Mean Diameter and hence the momentum equations of gas and liquid phase are derived.The momentum equations for gas phase and liquid phase in an arbitrary *i* direction are given in (16) and (17) respectively.

$$\frac{dv_i}{dz} = \frac{3Q_c C_D w_r \left(v_z - u_z\right)}{8 v_i u_z \Delta A D'} - \frac{v_i}{z} \quad (16)$$

$$\frac{du_i}{dz} = \frac{3\rho_a C_D w_r \left(v_i - u_i\right)}{4\rho_c D' u_i} \quad (17)$$

The velocity profiles can be solved using numerical methods and as they are a function of D', an initial guess of D' is made and the velocity profiles obtained are substituted for the new D' value and hence and the model is solved by iterative methods.

2.2 Results

Table 1. Comparison of Experimental and Predicted Values

Air Pressure (bar)	Coolant Flow rate (ml/hr)	Experimental D' (μm)	Predicted D' (μm)
2	60	23.7	12.6
2	80	12.9	8.8
2	100	7.0	4.8
4	60	18.3	16.5
4	80	7.5	6.5
4	100	4.0	2.8
6	60	16.3	12.6
6	80	6.8	3.3
6	100	2.0	1.2

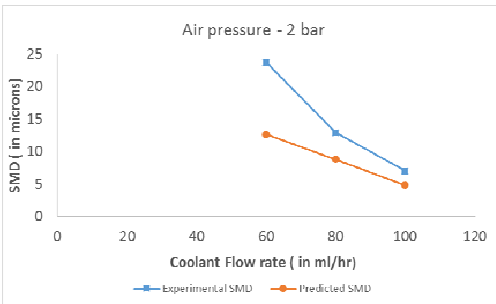

Fig. 2. Variation of D' with Coolant Flow rate at 2 bar

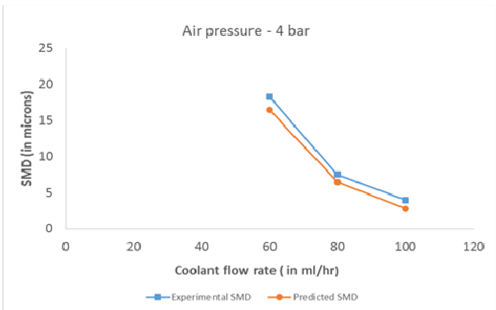

Fig 3. Variation of D' with Coolant flow rate at 4 bar

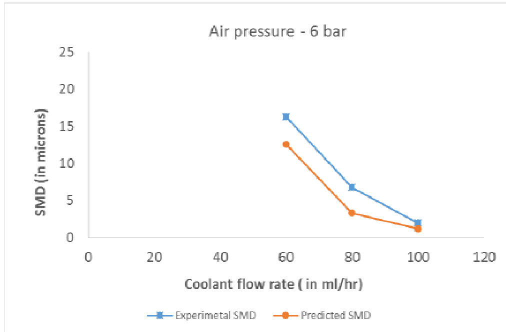

Fig. 4. Variation of D' with Coolant Flow rate at 6 bar

Thus the analytical model to determine the Sauter Mean Diameter of droplets in Air Assisted Atomizers for MQL applications in machining is developed and it is validated with the experimental results obtained by A.S.S.Balan et al.[9] . From the graphs it can be seen that the model correlates with experimental values with reasonable accuracy.

From the trend shown in the results, we can clearly infer that the increase in air pressure has resulted in reduction in the droplet diameter. Higher pressure results in greater kinetic energy of air and hence the more droplets (more surface energy needed) can be created and hence the size of the droplets is reduced

Also we can infer that rising coolant flow rate results in a drop in the droplet diameter. This can be justified with the argument that, greater flow rate indicates greater velocity of the coolant and hence the relative velocity between air and the droplets is reduced. This helps in reducing the drag work required and thus a greater part of kinetic energy is available for the creation of new surfaces and consequently more droplets.

3. Conclusion

Thus, in this paper an analytical model to determine the Sauter Mean Diameter as a function of the spray parameters is developed.

- This model can serve as the base to determine the optimum range of the input spray parameters for MQL applications in various machining processes.

- The model has experimental dependence in the case of constants required for viscous dissipation and for determining the initial velocities in the droplet regime.
- The model could not account for turbulence and hydrodynamic instabilities and it assumed drag coefficient for droplet spheres, neglecting droplet deformation.
- The advantage of this model is that it is universal for all machining processes and thus it eliminates the need for carrying out separate experiments to determine the optimal spray parameters for each type of machining operation and hence enhances the feasibility of MQL to be applied unanimously by all manufacturers shedding their doubt over the machining results (or) performance with application of MQL.
- Thus it is believed that the development of this model is one small step towards achieving sustainability in manufacturing, making it green, environment friendly and worker friendly and at the same time being economic for the manufacturers.

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Nomenclature

d_v -Number of droplets per unit volume (/mm^3)
Q_c -Volume flow rate of coolant (mm^3/s)
u_z -z-velocity of droplets (mm/s)
D -Droplet diameter (mm)
N -Number of droplets
R -Radius of the spray cone (mm)
ΔKE_a -Rate of change of Kinetic Energy of Air (kg mm^{2}s^{-2})
W_d -Drag Work (kg mm^{2}s^{-2})
S -Surface Energy rate (kg mm^{2}s^{-2})
V -Viscous Dissipation rate (kg mm^{2}s^{-2})
ρ_a -Density of Air (kgmm^{-3})
Q_a -Volume flow rate of Air (mm^3/s)
σ -Surface Tension (kgs^{-2})
D' -Sauter Mean Diameter (mm)
F_D -Drag Force (kgmms^{-2})
w_r -Relative velocity (mm/s)
C_D -Drag coefficient
μ_a -Dynamic Viscosity of Air (kgmm^{-1}s^{-1})
X -Experimental Constant
v_z -z-velocity of Air (mm/s)
v_r -r-velocity of Air(mm/s)
u_r -r-velocity of droplets (mm/s)
A -Cross sectional area (mm^2)