Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Thermal Analysis of Abrasive Waterjet Machining Process

Ngangkham Peter Singh, D. S. Srinivasu, *N. Ramesh Babu
Manufacturing Engineering Section, Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai - 600 036, India

Abstract

Abrasive waterjet machining is considered to be a cold machining process since the temperatures attained during cutting may reach around 60-70°C due to the interaction of the jet with the target material. Although the rise in temperature is very small, it becomes critical while machining thermally sensitive materials such as explosives, radioactive materials and bio-materials. As the interaction time between the abrasives and the target material falls in the range of micro-seconds, it becomes important to determine the intensity of heat flux generated during this time frame so as to avoid any explosion and to safeguard the material. In this work, an attempt to analytically model the heat flux developed on the cutting front surface, peak temperature generated and temperature distribution was made. This approach assumes the heat developed during the material removal phenomena through plastic deformation while high velocity waterjet serves as coolant removing the heat through convection. Peak temperatures obtained with this model were compared with the experimental results available in the literature.

Keywords: Abrasive waterjet, high energy materials, heat flux.

1. INTRODUCTION

In the current scenario, decommissioning of ammunitions has become one of the major objectives to safeguard environmental threats that can be caused due to accumulation of ammunitions. Among the various methods of dismantling, abrasive waterjet (AWJ) is considered to be a suitable method for dismantling and defusing ammunitions safely as the process does not induce much heat and does not change the phase of the material being processed. As this process is found to rise the temperature to about 60-70°C [9], it does not alter the phase of the material. However, the heat generated is sufficient to cause damage to highly sensitive materials such as explosives, radioactive materials and bio-materials. Knowledge about the heat generated at the machining zone was required for cutting such materials safely.

Attempts were made at various locations to measure the temperature using thermocouples [10, 11] and infrared thermography [10] and are reported to be in the range of 45°-70°C for aluminum and titanium alloys. Further, attempts were made to determine the heat flux generated at the interface by applying inverse heat conduction method and the temperature distribution along traverse and perpendicular directions are obtained by considering it as direct heat conduction problem [10]. However, the cause of generation of heat flux during the AWJ machining process is not addressed in the literature. For the purpose of predicting the heat flux generated, peak temperatures and the distribution of temperatures on work surface, various parameters of the process such as waterjet pressure (P), traverse rates (v), abrasive mass flow rate (m_a) and nozzle diameter (d_n) were considered. In this work, an attempt is made to predict the amount of heat flux developed at the interacting face considering the heat developed at the interface due to plastic deformation and cooling effect of the high velocity waterjet carrying the heat out of this interface through forced convection. Further, an attempt was made to predict the heat flux developed at the interface while making through cuts and blind cuts with different water jet pressure and jet traverse velocities.

2. MODELING APPROACH

Figure 1 shows the sources of heat generation and dissipation to determine the effective heat developed at the interface during AWJ machining process. Heat was considered to be added to the system in two ways i.e., during material removal process through plastic deformation and friction between abrasives and the workpiece. The later phenomenon was neglected in this study. For determining the heat developed during material removal process, both through cuts and blind cuts were considered. Heat developed during through cuts was based on specific cutting energy consumed. The kinetic energy associated with the abrasives was considered to estimate the heat generated during blind cuts.

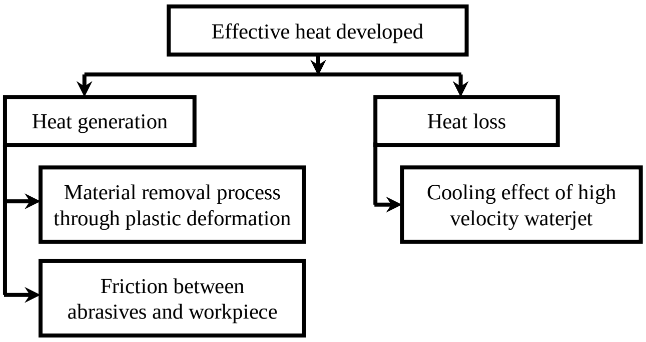

Fig.1. Sources of heat generation in AWJ machining process

Figure 2 shows the sectional view of AWJ cut surface, showing the interaction area (A) considered for cooling effects due to convection. The net heat flux generated was determined from these considerations and isotherm lines were obtained from the model.

2.1 Heat generated by material removal

In AWJ machining process, the removal of material occurs due to the impact of high velocity abrasives on the workpiece. Material plastically deforms during machining and produces heat. Using Bernoulli's equation and momentum transfer equation, the velocity of abrasives (v_a) is estimated and is given by

$$v_a = \eta_T \frac{1}{1+R} \mu \sqrt{\frac{2\,P}{\rho_w}} \qquad (1)$$

Where, η_T is the momentum transfer efficiency, R is the ratio of abrasive mass flow rate to water mass flow rate, μ is the discharge coefficient, P is waterjet pressure and ρ_w is the density of water. The value of μ and η_T are considered as 0.915 and 0.75 respectively.

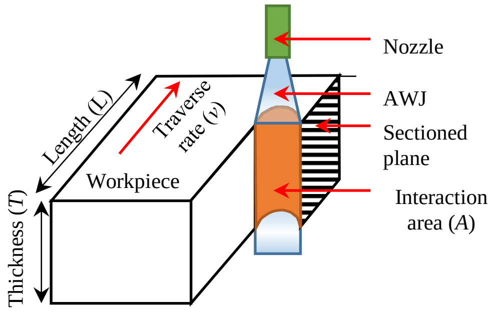

Fig. 2. A view showing the cross section of AWJ cut surface

2.1.1. Heat generated during material removal for through cuts

Characteristic time (t) defined as the time required for traversing a distance equal to jet diameter was considered for calculating the heat flux per unit time. For through cuts, the volume of material removed (V_R) during t seconds can be derived from

$$V_R = D_n^2\,T \qquad (2)$$

Energy consumed (Q_C) for eroding V_R of the material can be estimated using the equation (3) and is treated as heat generated during the process. U_{SP} for this process is considered to be the energy required for melting the workpiece [8] and the same is used in this work.

$$Q_C = V_R U_{SP} \qquad (3)$$

Rate of heat flux generation due to plastic deformation due to the impact of abrasives on the workpiece for through cuts can be expressed as

$$\dot{q}_C = \frac{Q_C}{A\,t} \qquad (4)$$

2.1.2. Heat generated during material removal for blind cuts

Only a fraction (F_1=0.83) of abrasives were considered to be effective for the material removal process. Hence, the total effective mass of abrasives involved during t seconds can be determined from the equation (5).

$$M_T = F_1\,\dot{m}_a t \qquad (5)$$

During the plastic deformation process, majority of the energy is dissipated in the form of heat and the rest in the form of strain energy due to dislocation, dislocation interactions and residual strains [13]. The amount of heat developed while deforming a body depends on several factors such as strain, strain rate and its material properties [3, 4, 7, 12]. Typically, stain rates more than 100 s^{-1} are considered high strain rates and strain rates for AWJ machining goes up to about $10^6 s^{-1}$ [6]. Fraction (β) of total mechanical work done on the system is dissipated as heat energy and is related to work done by the equation (6).

$$Q_{Plastic} = \beta\,\frac{M_T\,v_a^2}{2} \qquad (6)$$

Where, β is dependent on material properties, strain and strain rates. For example: 100% of work done is converted to heat for certain materials such as Ta-2.5% W, commercially pure Ti, 1018 steel and 6061Al [3] while it is reported to be in the range of 0.5-0.9 and closely agrees with the model proposed by Zehnder [9]. Widely accepted value for β lies in between 0.85-0.95 for most metals [1] and this value of 0.9 is considered in this work. Heat flux generated is determined from

$$\dot{q}_{Plastic} = \frac{Q_{Plastic}}{A\,t} \qquad (9)$$

2.2 Convective heat transfer by high velocity waterjet

Temperature of water exiting from intensifier is increased by 15K and is independent of the intensity of final pressure of water [2]. Further, the temperature along the length of the mixing tube increases by about 10K degrees while the temperature at the catching vessel increases by about 15K for every 100MPa increase in waterjet pressure and increases up to about 343-353K for operating water pressure of 300MPa [2]. This shows that high velocity waterjet acts as a source for removing heat from the workpiece during cutting operation.

Assuming that the flow is over a flat plate, Reynolds number determined shows that the flow is laminar. Hence, the forced convective heat transfer due to the jet was calculated accordingly. By applying the energy balance and equating the heat gained by the workpiece and the heat lost by the waterjet during dt seconds, the heat loss generated can be determined by the equation (10)

$$Q_{Water} = h\,A\,(T_W - T)dt = m\,C_P dT \qquad (10)$$

By simplifying the equation (10), integrating from 0 to t seconds and applying the boundary conditions.

At $t=0$, $T = T_i$
At $t=t$, $T = T(t)$

$$\frac{T(t) - T_W}{T - T_W} = e^{-b\,t} \qquad (11)$$

Where, $b=h\,A/\rho_M\,V_M\,C_{P,M}$, $T(t)$ is the temperature of the body at t seconds, T is the initial temperature of workpiece, T_W is the temperature of the fluid, h is the forced convective heat transfer coefficient, ρ_M is the density of workpiece material, V_M is the volume of material considered to be heated at the same temperature during time t and $C_{P,M}$ is the specific heat for the workpiece material. For simplicity, V_M was considered to be volume of a solid cylinder with twice the jet diameter and with a thickness of t_1. $T(t)$ was determined by using the equation (11) and the same was used to determine the heat transferred to the body during t seconds. The value of h can be estimated from Nusselt number (Nu) and Prandtl number (Pr) for laminar flows.

$$N_u = \frac{h\,l}{k} = 0.664\, R_e^{\frac{1}{2}}\, P_r^{\frac{1}{3}} \qquad (12)$$

$$P_r = \frac{\gamma}{\alpha} = \frac{\mu\, C_p}{k} \qquad (13)$$

Where, 'l' is the characteristic length and is defined as the ratio of cross sectional area to perimeter, 'k' is the thermal conductivity of the fluid, 'R_e' is Reynolds number, 'γ' is kinematic viscosity, 'μ' is dynamic viscosity and 'C_p' is the specific energy at constant pressure. Taking initial water temperature as 298.15K, water temperature after compression was considered to be dependent on the P used. The estimated value of h was considered for simulating the temperature profiles with different process parameters.

2.3 Simulation study

Heat generated by material removal is taken as heat source while the heat carried away by waterjet interacting with the workpiece is taken as heat sink. Table 1 shows the range of process parameters used for this simulation [5]. Time dependent deformed geometry and heat transfer in solid modules available in COMSOL 5.1 were used for simulating the temperature distribution at the machined interface. Deformed geometry modules defines the deformation based on the geometry frame alone and was found suitable for this study.

Table 1. Process parameters used for validating the study

Process parameter	Value
Workpiece	
Material	Al 2024
Thermal conductivity (W/m-K)	177
Thermal diffusivity (m^2/s)	73.0 x 10^{-6}
Volumetric heat capacity (MJ/m^3-K)	2.424
Density (kg/m^3)	2780
Abrasive waterjet	
Pressure, P (MPa)	241, 276, 310
Orifice diameter, d_o (mm)	0.254
Nozzle diameter, d_n (mm)	0.762
Abrasive (80#) flow rate, $\dot{m}_a$ (kg/min)	0.681
Traverse rate (mm/s)	0.85, 1.06, 1.27
Stand-off distance, SoD (mm)	4
Workpiece dimension (mm)	46.0 x 25.4

For simulating this process, an additional length equal to distance to be traversed during the total time required for traversing total length of workpiece was considered. This was necessary as generation of different domain would yield erroneous deformed geometry and not applicable for this study. Velocity of the arc was taken to be the traverse rate at which the nozzle moves along x axis, while restricting all other directions. Displacement of the guiding faces was restricted along y and z axes. Deformed geometry was first solved in order to obtain deformed coordinates and then linked to heat transfer module to determine temperature distribution.

Heat flux obtained for through cut approach was found to be 0.885 MW/m^2 for different P. Heat flux generated for different P were constant as the same volume of material was removed in this case. Heat flux generated for blind cut approach was found to be 16.43 MW/m^2, 19.06 MW/m^2 and 21.63 MW/m^2 for P of 241MPa, 276MPa and 310MPa respectively. Heat flux determined was applied as boundary heat source on the interacting face. The value of h was found to be 313871W/m^2-K for the flow and applied as forced convection on A. Remaining edges were kept as open boundary. Free tetrahedral mesh was used with minimum mesh size of 0.2mm. Time step for the simulation was chosen as $t/5$ and the total time of simulation was found to be the time required for the jet to traverse over a length 'L'. MUMPS algorithm was used as the solver. Initial workpiece temperature was considered as 298.15K.

3. RESULTS AND DISCUSSION

Maximum temperature obtained and temperature profiles obtained from the simulation are compared with experimental results from the literature [5]. Figure 3 and 4 show isothermal lines and maximum temperatures obtained after simulation at 23.57 seconds on the workpiece cut with a traverse velocity v of 1.06mm/s and *water jet pressure* of 310MPa obtained for through cuts and blind cuts. It was observed that through cut approach led to the prediction of lower temperature than that obtained with the blind approach. This was due to higher heat flux supplied on the interacting face A for blind cuts approach as compared to through cuts approach. Figure 5 shows the increase in peak temperatures obtained with variation in waterjet pressure P. This was due to the application of higher heat flux at the interface in addition to the increase in water temperature with waterjet pressure. Blind cut approach was found to predict with maximum accuracy of 1.21%, while through cut approach predicted with maximum accuracy of 1.51%. Non-linearity behavior of peak temperature with increase in pressure was not captured in this modeling approach.

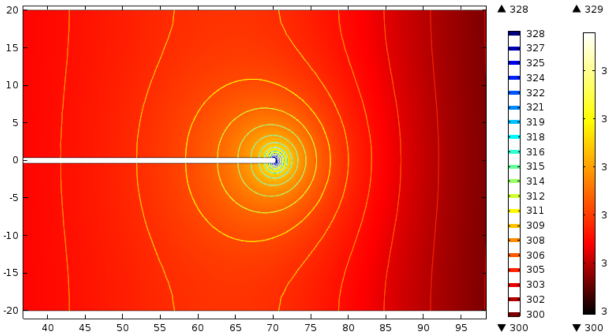

Fig.3. Isothermal line and peak temperature (K) obtained for waterjet pressure of 310 MPa and traverse rate of 1.06mm/s for through cuts.

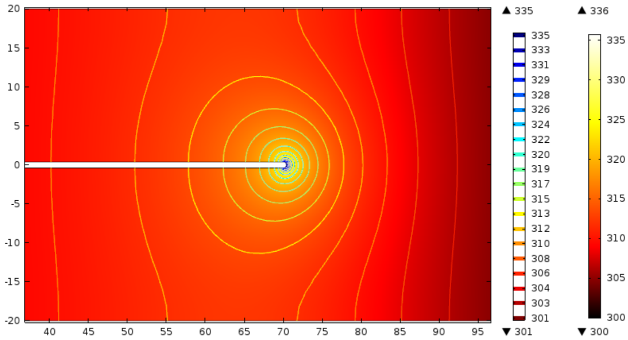

Fig.4. Isothermal line and peak temperature (K) obtained for waterjet pressure of 310 MPa and traverse rate of 1.06mm/s for blind cuts.

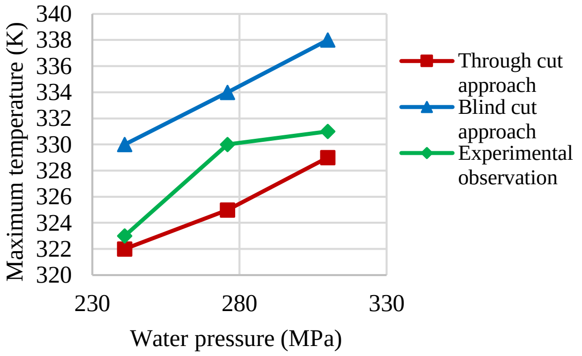

Fig.5. Maximum temperature variation with change in operating waterjet pressure

Figure 6. shows the variation in maximum temperature obtained with variation in traverse rates. It was observed that variation in traverse rates does not alter the peak temperatures and had less effect. Through cut approach was found to predict with average accuracy of 0.8%, while blind cut approach predicted with average accuracy of 1.83%. Through cut approach was not able to capture the sharp increase in maximum at higher traverse rates.

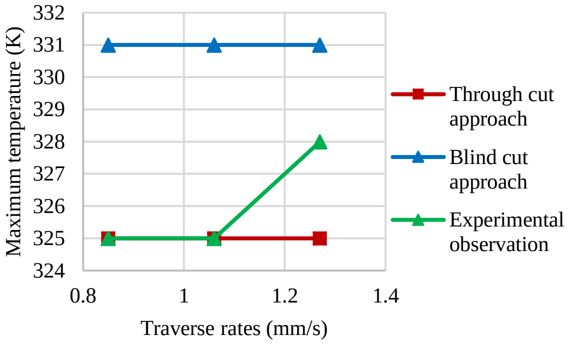

Fig.6. Maximum temperature variation with change in traverse rates

Experimental measurements gave non-linear relationship with waterjet pressure and maximum temperature observed in the workpiece. Similar observations were also visible with variation in traverse rates as well. Predicted values of peak temperatures varied linearly increased with increase in pressure and traverse rates. This suggests that more physics is involved in this process which are not included in this paper.

4. CONCLUSION

An analytical model was developed for determining the heat flux at the contact surface. Maximum temperatures and isotherms was determined by simulating using COMSOL. Out of the two approaches used, i.e., through cut approach and blind cut approach, accuracy of the former was higher for predicting peak temperatures for varying waterjet pressures. On the other hand, blind cut approach predicted peak temperatures with higher accuracy. Results indicates the possibility of application of this approach for predicting the temperature distribution and peak temperature. Non-linear pattern observed in the experimental values was captured in this model and considered as scope for future work.

References

[1] Fekete, B., & Szekeres, A. (2015). Investigation on partition of plastic work converted to heat during plastic deformation for reactor steels based on inverse experimental-computational method. *European Journal of Mechanics-A/Solids*, 53, 175-186.

[2] Jerman, M., Orbanic, H., Etxeberria, I., Suarez, A., Junkar, M., & Lebar, A. (2011). Measuring the water temperature changes throughout the abrasive water jet cutting system. In *2011 WJTA American waterjet conference* (p. 12).

[3] Kapoor, R., & Nemat-Nasser, S. (1998). Determination of temperature rise during high strain rate deformation. *Mechanics of Materials*, *27*(1), 1-12.

[4] Knysh, P., & Korkolis, Y. P. (2015). Determination of the fraction of plastic work converted into heat in metals. *Mechanics of materials*, *86*, 71-80.

[5] Kovacevic, R., Mohan, R., & Beardsley, H. E. (1996). Monitoring of thermal energy distribution in abrasive waterjet cutting using infrared thermography. *Journal of Manufacturing Science and Engineering*, *118*(4), 555-563.

[6] Li, W., Zhu, H., Wang, J., Ali, Y. M., & Huang, C. (2013). An investigation into the radial-mode abrasive waterjet turning process on high tensile steels. International Journal of Mechanical Sciences, 77, 365-376.

[7] Hodowany, J., Ravichandran, G., Rosakis, A. J., & Rosakis, P. (2000). Partition of plastic work into heat and stored energy in metals. *Experimental mechanics*, *40*(2), 113-123.

[8] Hoogstrate, A. M., Karpuschewski, B., Van Luttervelt, C. A., & Kals, H. J. J. (2002). Modelling of high velocity, loose abrasive machining processes. CIRP Annals-Manufacturing Technology, 51(1), 263-266.

[9] Macdougall, D. (2000). Determination of the plastic work converted to heat using radiometry. Experimental mechanics, 40(3), 298-306.

[10] Ohadi, M. M., & Cheng, K. L. "Modeling of temperature distributions in the workpiece during abrasive waterjet machining". *Journal of heat Transfer*, *115*(2), 446-452, 1993.

[11] Ohadi, M. M., & Whipple, R. L. (1991). Measurement of temperatures in a tubular workpiece during cutting with an abrasive waterjet. *Experimental Techniques*, *15*(4), 38-42.

[12] Rittel, D. (1999). On the conversion of plastic work to heat during high strain rate deformation of glassy polymers. *Mechanics of Materials*, *31*(2), 131-139.

[13] Zehnder, A. T. (1991). A model for the heating due to plastic work. *Mechanics Research Communications*, *18*(1), 23-28.