Safety Analysis on Abrasive Water Jet Use under Flammable Gas Condition

By : Brianto Usman, 76756, Dept. Environment Systems, March 2009 Graduation
Supervisor : Associate Prof. Sohei Shimada

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1. Introduction:

Abrasive Water Jet (henceforth, AWJ) is a cutting device in which water is pressurized to over 500 MPa, mixed with abrasive materials and sprayed through a nozzle with orifice of 0.1-2.0 mm with a velocity near the speed of sound ($340ms^{-1}$). Abrasive materials such as Garnet ($Al_2O_3.3FeO.2SiO_2$) or olivine sand (42~48% MgO, 33~42%SiO_2) are used to enhance the cutting performance. Nowadays, water jets are used in the manufacturing, mining, construction and environment field. (Environment field: Asbestos removal and Polluted soil remediation).

Usage of AWJ for rescue operation of an accident is considered after JR Amagasaki derail train accident, Hyogo April 25th 2005. The front compartment of the train crashed into the parking lot in 1st floor mansion. Gasoline leaked from the car tank and evaporated, creating a flammable gas condition in the accident site. Normal cutting device such as burner or diamond cutter could not be used due to the possibility of gasoline ignition. This resulted in a difficult manual rescue operation which lasted for 82 hour long. As a solution to this problem, usage of AWJ device is considered.

However, the generation of spark from abrasive material impact during AWJ use is typically known. Compared to other cutting devices, AWJ spark energy is considerably small and by use of water, ignition toward flammable gas can be prevented significantly. This research main purpose is to analyze the safety level of AWJ spark by : 1) AWJ device experiment, 2) Grinder experiment and 3) Theoretical ignition model.

2. AWJ Spark and Ignition Experiment

Cobra Diajet 690 AWSJ was used with olivine sand abrasives. The device consists of pump module and slurry module. Water is passed through 20μm filter and pressurized by 7 kW diesel engine to 69MPa in the pump module. It is then sent to the slurry module with max 5.5L/min to obtain a 12% abrasive concentration. The nozzle with orifice of 0.55 mm is set inside the anti-explosion chamber for flammable gas (methane) experiment.

Metal alloy SS400, S45C, SUS304, Aluminium, A1100P, Copper samples were used. Only steel alloys SS400 and S45C emitted sparks. Sample with hard surface, small impact angle and threshold of the standoff distance generates most sparks. Thus, sparks are considered small metal fragment from hard surface which experienced localized temperature rise.

Methane gas experiments (6 times/ conc.8%-12%) were conducted in the most spark generating condition : S45C, 30° impinging angle (toward surface), and 20 cm standoff distance. The AWJ sparks did not lead to any methane ignition.

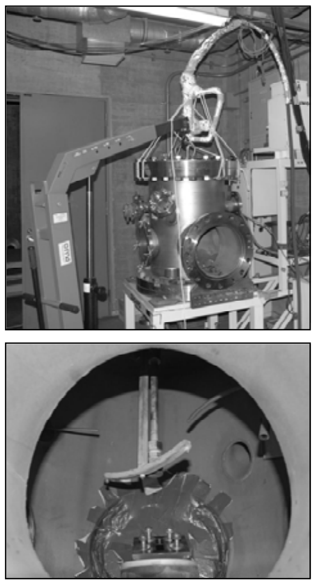

Photo 1. Experiment Setting

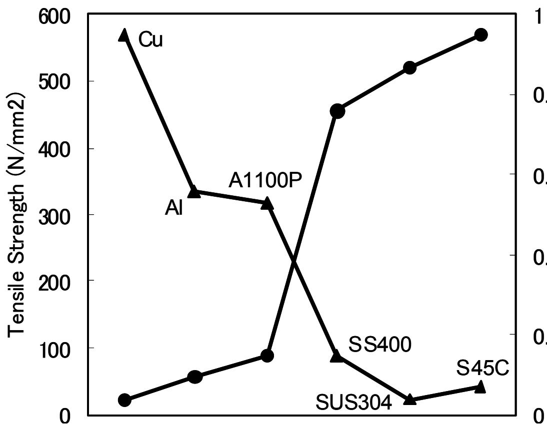

Fig.1 Mechanical Properties of Alloy

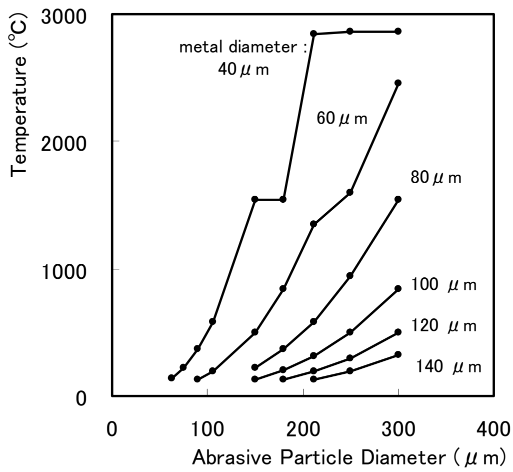

Fig.2 Calculated AWJ Spark Temperature

To analyze the safety of AWJ sparks, temperature is calculated from the following method. Olivine sand particle diameter is measured and its kinetic energy can be calculated by using slurry velocity at the nozzle $v_0 = (2P_0/\rho)^{1/2}$. From the video data, the spark size is measured and metal size is predicted to be 10% of the spark size (by comparison between video data and microscope measurement of metal fragments). During the impact, the kinetic energy from the abrasive particle is converted into heat energy of metal for temperature rise. $(E_{Kinetic} \to E_{Heat})$

$$\tfrac{1}{2} m_{abrasive} v_{spray}^2 \to (mc\Delta T)_{solid} + mL_f + (mc\Delta T)_{liquid} + mL_v + (mc\Delta T)_{gas}\Big|_{iron}$$

Methane flammability limit is 5%-15% and ignites most easily at 7%. Previous studies shows that 1000℃ is necessary for methane ignition [2]. However, in the calculation with 100% kinetic energy to heat energy convergence, the possibility that AWJ spark exceeds 1000℃ is only 4.59%. Furthermore, by considering the energy used for metal deformation and the effect of water, lower spark temperature will be obtained.

3. Friction Spark – Grinder Experiment

To observe the necessary condition for ignition, friction spark-grinder device was built. Vessel length 80 cm, diameter 50 cm, with grinder 10.5 diameter is used. Nozzle 45μm is set in the ceiling for gasoline and water spray. Fan is set at the bottom for creating a uniform mixture. The sample is set to oil-pressurized cylinder capable of front-rear movement. Grinder and fan are controlled by wind pressure from a compressor 0.8Mpa. Samples used are similar to AWJ experiment : SS400, S45C, A1070B, A5056B, A7075, C1100B, Mg.

Alloy	Methane	Propane	Gasoline	
SS400	12.3%	4.1%	Direct spray 0.6MPa	
	20sec	68sec	30sec	
	10.5%		1.8%	
	50sec		78sec	68sec
	9.5%		3.2%	
	40sec		98sec	37sec *
			3.6%	
			66sec	17sec *
S45C	10.5%			
	50sec			
A5056	9.4%	4.20%		
	No Spark	No Spark		

Table 1 Flammable Gas Concentration and Spark Time
* Ignition Occurrences

Only steel alloys SS400 and S45C produce sparks. Experiment using olivine sand attached to the grinder show that olivine sand produces less sparks. Thus, by observing the ignition threshold from friction spark in this experiment, AWJ sparks safety level from previous experiment can be analyzed. Experiment condition using flammable gas is summarized in Table 1. No ignition was observed toward methane or propane. Gasoline is more ignitable with 30% of ignition probability.

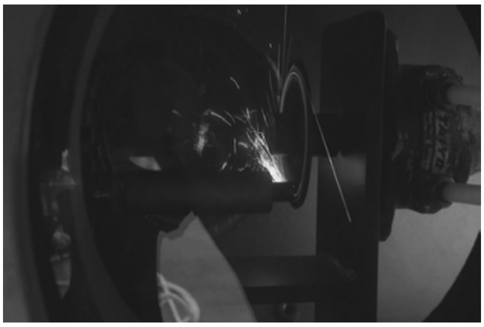

Photo 2 No Ignition in propane 4.1%, 1600rpm

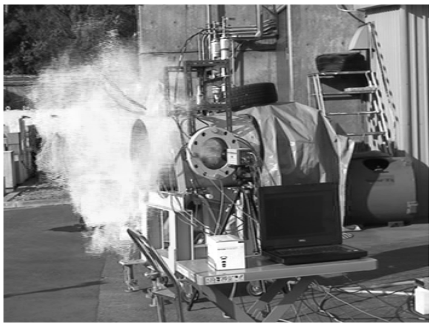

Photo 3 Ignition of gasoline 3.6%

The sparks generated in this experiment has more energy and higher temperature compared to AWJ sparks. However, it did not lead to ignition of methane or propane and only 30% ignition probability in gasoline. By this experiment, the safety of AWJ spark is assured and its probability of flammable gas ignition is low.

4. Theoretical Model of Ignition Temperature

The ignition temperature of a fuel depends on the size (area) of the heat source and can be calculated analytically. For calculation concerning methane gas, the following assumptions are made: 1) Heat source has a stable temperature independent of time. 2) Air mixture physical properties are used for methane / air mixture properties. 3) Elementary reactions are omitted and only one-step reaction is considered during combustion.

The proposed calculation method is given as following:

Heat transfer equation : $k\frac{d^2T}{dx^2} + Qr_f = 0$、 reaction rate $r_f = -X_f^{m_f} X_O^{m_O} \rho^n A e^{-E/RT}$

By integrating the above equation over T with boundary condition $x = 0, T = T_{ignite}$ (Ignition temperature), $x = \delta, T = T_R$ (Room Temperature), the heat from chemical reaction can be expressed as:

$$q_{chem} = k\frac{dT}{dx} = \left[2kAX_f^{m_f} X_o^{m_o} Q\rho_e^n \left(T_{ignite}/T_R\right)^{n/2} \left(RT_{ignite}^2/E\right) e^{-E/RT_{ignite}}\right]^{1/2}$$

Heat loss from the surface : $q_{loss} = kNu(T_{ignite} - T_R)/L$ 、
with characteristic length L = area/perimeter.

Nusselt number is obtained empirically and given by Churchill Chu[1]

$$\overline{Nu}^{1/2} = 0.825 + 0.305Gr^{1/6} \text{、} \quad Gr = g\beta L^3 v^{-2}(T_{ignite} - T_R)$$

By applying Van't Hoff Criterion （At ignition the rate of heat loss to surroundings is equal to the rate of heat gain by chemical reaction）

$$\left({}^{dT}\!/_{dx}\right)_{wall} = 0 \quad 、 \quad q_{chem} = q_{loss}$$

By combining the above equations, relation between ignition temperature T_{ignite} and characteristic length L is given by solving a polynomial equation:

$$0 = 0.681 + f_1\sqrt{L} + f_2 L$$

$$f_1 = 0.503\left({Gr}/{L^3}\right)^{1/6} \quad 、 \quad f_2 = 0.093\left({Gr}/{L^3}\right)^{1/3} - \frac{q_{chem}}{k\left(T_{ignite} - T_R\right)}$$

where f_1 and f_2 is an equation of ignition temperature.

In square shaped object, area is given by L=Area/Perimeter=$L^2 / 4L$, thus Area=$4L$

5. Conclusion

AWJ spark safety is analyzed by experimental and mathematical method. As shown in the Fig 5. , methane requires 1000℃for ignition. However, comparison shows that most of AWJ spark temperatures are lower than the theoretical ignition line. Thus, ignition probability to methane from AWJ spark is low.

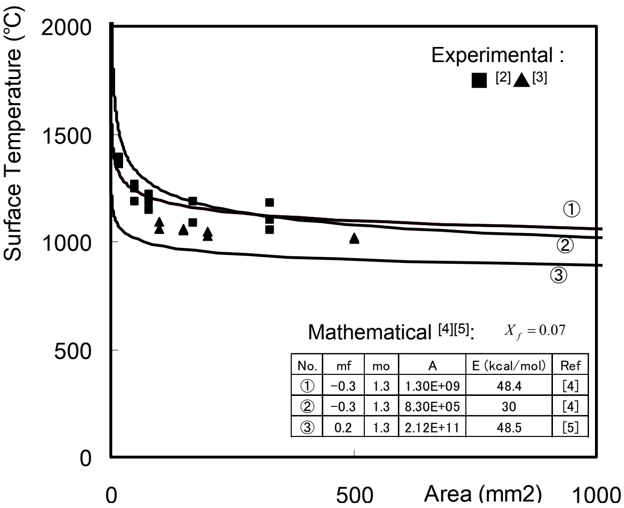

Fig. 3 Methane calculated ignition temperature

6. Future Works

Gasoline is more ignitable compared to methane or propane. Thus, further analysis with consideration of water existence is essential. Analysis on other fuel such as hydrogen is also necessary.

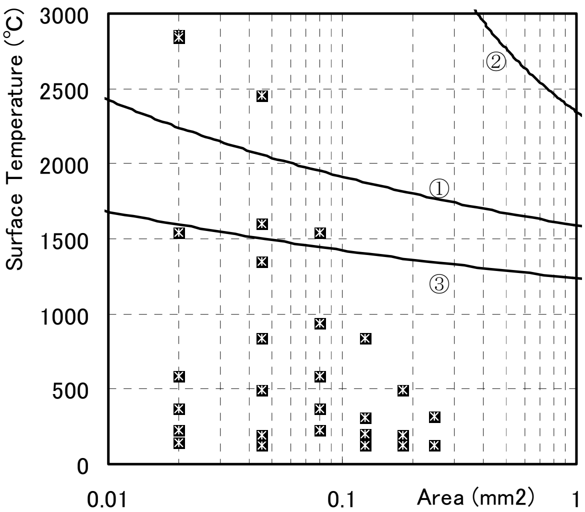

Fig. 4 Comparison with AWJ sparks temperature. Line: methane; Dots: AWJ sparks

7. Reference

[1] S.W. Curchill, H.H.S. Chu, *Intl.J.Heat and Mass Transfer*; Vol.**18** (1975) 1323-1329.

[2] N.M. Laurendau, *Combust. Flame* **46** (1982) 29-49

[3] N.M. Laurendau, *Combust. Flame* **46** (1982) 213-218

[4] C.K.Westbrook, F.L. Dryer, *Prog. Energy. Combust. Sci.* **18** (1984) 1-57

[5] J. Lindberg, R. Hermanson. *Energy & Fuel* **18** (2004) 1482-1484