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Some Studies on Abrasive Jet Machining

A machining operation is basically a material removal process, where material is removed in the form of chips. In a machining operation, the output parameter is achieved by controlling various input parameters. This paper discusses the effects of various input parameters in abrasive jet machining (AJM) on the material removal rate (as the output parameter). The results presented in the paper are obtained from an experimental study carried out with an AJM unit with vortex type mixing chamber. The study was restricted to abrasive jet drilling only.

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Introduction

Abrasive jet machining (AJM) is a process of material removal by mechanical erosion caused by the impingement of high velocity abrasive particles carried by a suitable fluid (usually a gas or air) through a shaped nozzle on to the workpiece.

An AJM set-up may be of two types : one employing a vortex-type mixing chamber and the other employing a vibratory mixer. In the former, abrasive particles are carried by the vortex motion of the carrier fluid, whereas in the latter type abrasive particles are forced into the path of the carrier gas by the vibrating motion of the abrasive particle container.

The erosion phenomenon in an AJM study may be considered in two phases. The first phase consists of transportation problem, that is, the quantity of abrasive particles flown, and the direction and velocity of impinging particles as determined by the fluid flow condition of solid-gas suspension. The second phase of the problem is the determination of the material removal rate or the erosion rate.

The erosion of a surface by impacting solid particles is a discrete and accumulative process. Hence, the models are first made on the basis of a single particle impact. The mechanism of erosion in such cases is complex, involving mechanical, chemical and material properties. The erosion is a function of several variables such as

(i) Speed and angle of impact;

(ii) Ductility and/or brittleness of the material and the impinging particles;

(iii) Elasticity of the material;

(iv) Shape and geometry of impinging particles;

(v) Impinging particle diameter to work-material, thickness ratio;

(vi) Average flow stress;

(vii) Material and density; and

(viii) Distance between the nozzle mouth and workpiece (known as the stand-off distance).

Finnie[1] had shown that $Q = \dfrac{C f(\theta) M V^n}{\sigma}$, where Q is the volume of material removed by an impacting particle of mass M carried in a stream of air expanding in a nozzle of fixed geometry; C and n, the constants; V, the velocity of impacting particle; θ, the impingement angle; and σ, the minimum flow stress of the target material. Subsequently Sheldon, *et al*[2] found the value of the impingement angle for which the volumetric material removal rate is maximum. For brittle materials, the impingement angle is 90° for maximum erosion rate while it is 20°-30° for ductile materials. Later, Sheldon and Finnie[3] proposed that the erosion occurs as a result of Hertzian contact stress which causes a crack to grow from a pre-existing flaw in the existing work-material. The stress at which the crack propagation occurs is related to the distribution of surface flaws through Weibull statistics, where it is assumed that the risk of rupture is proportional to a function of the stress and the volume of the body. They further showed that the velocity exponent in the erosion equation is a function of the flaw parameter of Weibull fracture strength distribution. Bitter[4] modified Finnie's erosion equation with the concept of a threshold particle energy below which 'brittle erosion' ceases and a minimum effective angle of impingement below which 'ductile erosion' ceases.

Neema and Pandey[5] proposed an equation for material removal rate by equating the kinetic energy of the impacting particle to the work of deformation during indentation. They gave

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$$Q = k\,N\,d^3\,v^{\frac{3}{2}}\left(\frac{\rho_a}{12\,\sigma_y}\right)$$

where k is a constant; N, the number of abrasive particles taking cut a time; d, the size or diameter of an abrasive particle; ρ_a, the density of the abrasive material; v, the velocity of the abrasive particle; and σ_y, the yield stress of the work material.

Pandey, *et al*[5,6] and Bhattacharya[7] studied the effects of abrasive flow rate (AFR) and stand-off distance on the material removal rate (MRR). They observed that MRR reaches an optimum value with the increase in AFR and SOD, and then falls with the increase in these parameters.

In case of micro-drilling, it is the erosion depth (or the depth of penetration) which is of importance. Verma and Lal[8] studied the effects of SOD on the penetration rate and cavity top diameter. They observed that penetration rate reaches an optimum value with the increase in SOD after MRR has reached its optimum.

In this paper, the effect of carrier fluid (air) pressure on the MRR, AFR, and the material removal factor (MRF) have been investigated experimentally on an indigenous AJM set-up developed in the laboratory.

Experimental Set-up

The nomenclature for an abrasive jet machining is shown in Fig 1 and the experimental set-up is shown schematically in Fig 2(a).

The compressed air from the compressor enters the mixing chamber partly prefilled with fine grain abrasive particles. The vortex motion of the air created in the mixing chamber carries the abrasive particles to the nozzle through which it is directed on to the workpiece. The nozzle and the workpiece are enclosed in a working chamber with a perspex sheet on one side for viewing the operation. The nozzle and mixing chamber are shown in Figs 2(b) and 2(c), respectively.

The abrasive particles used were SiC (grain size 60 microns and 120 microns). The nozzle material was stainless steel and the nozzles used were of diameters 1.83 mm and 1.63 mm.

This type of set-up has the advantage of simplicity in design, fabrication and operation. The equipment cost is much less except the compressor. The mixture

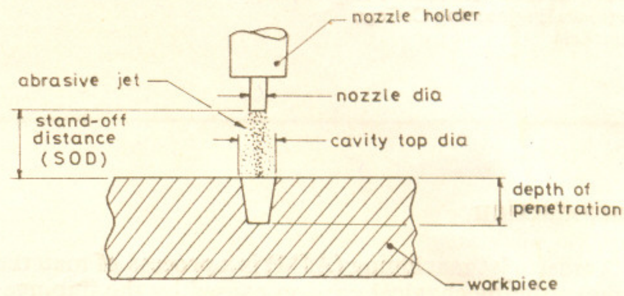

Fig 1 AJM nomenclature

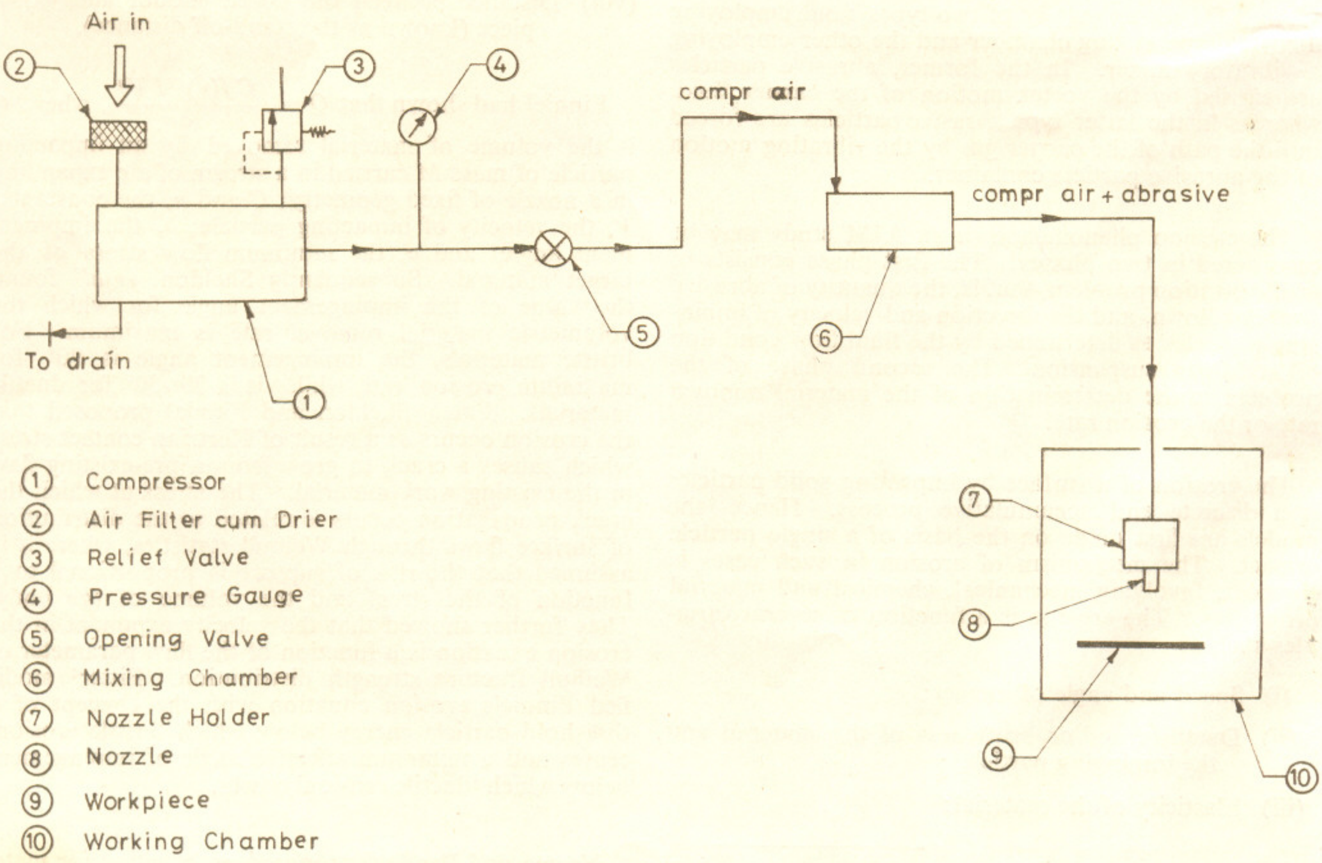

Fig 2 (a) Schematic diagram of experimental set-up

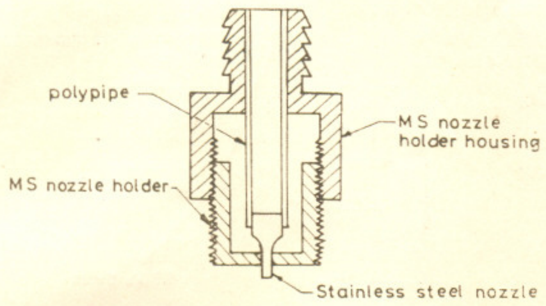

Fig 2 (b) Nozzle assembly

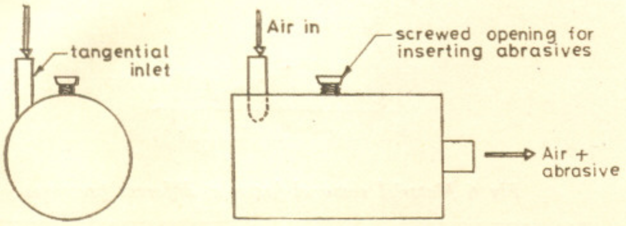

Fig 2 (c) Vortex type mixing chamber

ratio is controlled by the inclination of the mixing chamber. The mixture ratio is defined as

$$\alpha \text{ (mixture ratio)} = \frac{\dot{m}_p}{\dot{m}_a + \dot{m}_p}$$

where $\dot{m}_p$ is the mass flow rate of the abrasive particles and $\dot{m}_a$ the mass flow rate of air.

Experimental Results and Discussion

The results are presented in the form of graphs. Figs 3(a) and 3(c) show the variation of MRR with air pressure. It is found that MRR increases with increase of air pressure and there is a threshold pressure below which MRR practically ceases. In fact, below this pressure there would be some amount of material removal which is small and negligible. It is also observed that MRR is increased with increase in grain size and increase in nozzle diameter. The dependence of MRR on stand-off distance reveals that MRR increases with increase in SOD at a particular pressure (Fig 5). However, from the work of other researchers[6–8], it is found that after the initial increase MRR remains almost constant for a small range and then falls as SOD is further increased.

Figs 4(a) and 4(b) show the effect of air pressure on abrasive flow rate. It is found that AFR $\propto p^{0.7 \sim 0.85}$. With the vortex motion of the air and fine grain abrasives, it is reasonable to assume that abrasive particles are carried as the pressure is increased from zero.

At this stage, a material removal factor (MRF) may be introduced. MRF is defined by

$$\text{MRF} = \frac{\text{MRR (g/min)}}{\text{AFR (g/min)}}$$

Thus, MRF is a non-dimensional parameter and it gives the weight of material removed per gram of abrasive particles.

Fig 6 shows that MRF decreases with increase in pressure, which means that the quantity of material removed per gram of abrasives at a higher pressure is less than the quantity of material removed per gram of abrasives at a lower pressure. The probable explanation to this phenomenon is that at higher air pressure more number of abrasive particles are carried through the nozzle which gives rise to more number of inter-particle collisions and hence more loss of energy. Also, the cushioning effect of the trapped abrasive particles inside the cavity (till the hole is drilled through) reduces the erosion capability of the oncoming stream of abrasive particles. The cushioning effect is directly comparable to that occurring in water jet machining, where it is found that the specific energy in cutting is lower than that required for piercing due to the fact that the groove generated in cutting allows for the 'counter flow' of the jet to escape freely with minimum tendency to build a 'liquid cushion[9,10] (specific energy is the energy required to erode unit volume of work-material).

With stainless steel nozzle, the nozzle life was found to be about 2 hr. However, increased nozzle life can be obtained with tungsten carbide (12-30 hr) and synthetic sapphire (300 hr) as the nozzle material[11].

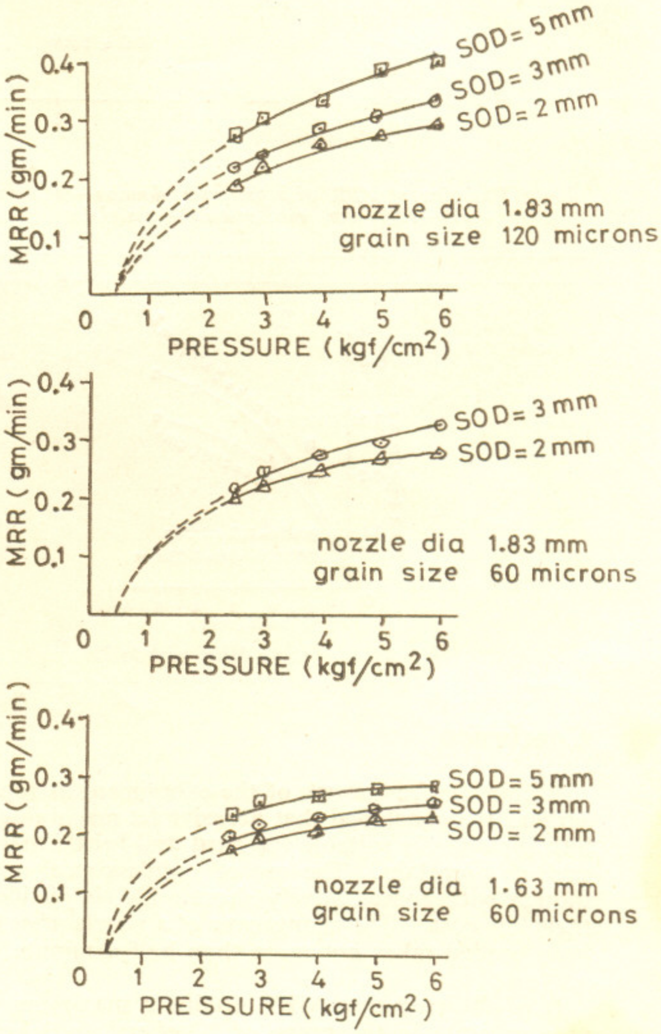

Fig 3 Variation of MRR with pressure abrasive—SiC, work material—porcelain

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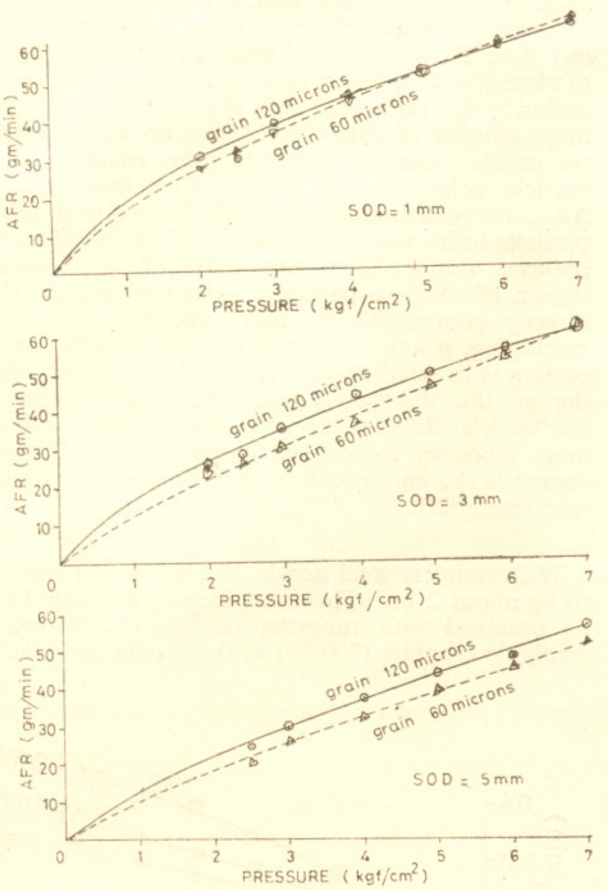

Fig 4 Variation of AFR with pressure: abrasive—SiC, nazzle dia—1.83 mm, work-material—procelain

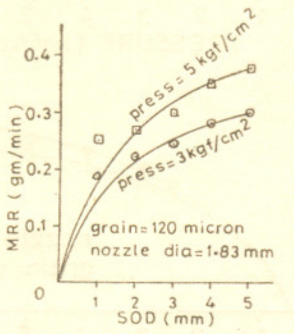

Fig 5 Variation of MRR with SOD

Conclusion

Within the framework of the experiment as reported earlier, it is concluded that abrasive jet machining with SiC abrasives is suitable for hard and brittle materials such as porcelain. The use of stainless steel nozzles, though with comparatively shorter life, is justified by their low cost. The changeover of a nozzle after it has been eroded takes not more than half a minute.

It is observed that MRF attains a maximum value at a pressure in the range of 2 kgf/cm² to 3 kgf/cm² (under the stated experimental conditions) and there is a marginal increase in MRR beyond 4 kgf/cm²

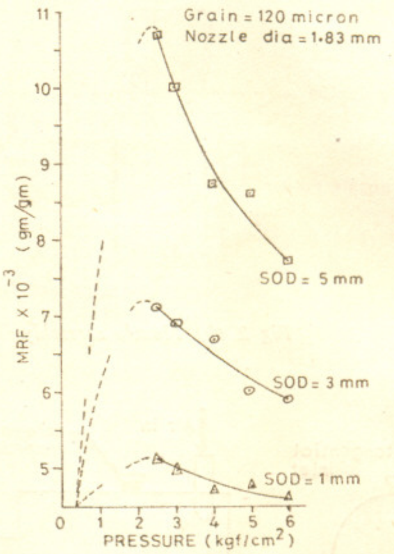

Fig 6 Material removal factor at different pressures

pressure. Hence, with this type of set-up and experimental conditions, a suitable operating pressure would be about 3 kgf/cm². Further, it is seen that MRF and MRR are more at higher stand-off distances. Thus, a higher stand-off distance would be preferable where material removal rate is of prime importance. However, in precision work a higher pressure and a lower stand-off distance may be adopted to attain a higher accuracy and penetration rate.

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