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Water Jet Machining—A State of Art

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With the advent of newer materials and intricate shapes of components, unconventional methods of material removal have been developed. Water jet machining (WJM) is one of such processes of material removal. This paper briefly describes the basic features of WJM, such as, its mechanism of material removal, advantages, and application possibilities.

INTRODUCTION

The principle of rain-erosion phenomenon occuring on high speed aircrafts is welknown and is utilised in high pressure jet cutting where a high pressure jet of small diameter is directed at a target material at a high velocity.

Water jet cutting (also called water jet machining or WJM) is similar to laser beam machining and electron beam machining in one respect. The similarity lies in concentrating a given amount of energy onto a small point to cause material removal.

The kinetic energy possessed by a jet increases in quadrature with the velocity. Hence in precision jet cutting with small diameter jets, though the mass flow rate is reduced, the kinetic energy possessed by the jet increases with the increase in velocity imparted by high pressure.

When a high velocity water jet is directed at a target in such a way that on striking the surface, the jet velocity is virtually reduced to zero, most of the kinetic energy possessed by the jet is converted into pressure energy. In fact, in the first few milliseconds after the initial impact the transient pressure generated may be as high as three times the normal stagnation pressure[1], the tansient spike being due to the water hammer effect.

The mechanism of jet-cutting is very complex. Material removal is done mechanically by erosion caused due to localised compressive failure which occurs when the local fluid pressure exceeds the ultimate compressive strength of the target material[2,3].

When a jet impinges a flat plate at right angles, the fluid spreads out radially over the plate from the centre of impact. The initial velocity of the outward flowing liquid is much higher than the impact velocity. The jet produces a shallow indentation on the surface of ductile materials and a ring fracture in brittle materials. The radial flow of liquid across the surface leads to erosive shearing along the edges of the deformed area. Even the smallest surface discontinuities act as nuclei for erosion pits. Thus in ductile materials surface depressions are eroded by the shearing action of the surface flow. The failure in brittle materials is by fracture whereas that in high strength alloys is probably due to fatigue[4].

When quality cutting is not involved, other mechanisms contribute, such as spalling caused by stress waves and the effect of stagnation pressure caused by the cutting fluid penetrating the cracks and pores. Some researchers feel that cavitation also plays a role in eroding the target material; it is known that cavitation collapse can give rise to pressures capable of eroding the strongest solids[2].

PROCESS PARAMETERS

For successful utilisation of WJM process, it is necessary to analyse the following process criteria:

(i) Material removal rate (MRR).
(ii) Shape and finish of the work-piece.
(iii) Wear rate of the nozzle (since the nozzle is costly item in the set-up requiring replacement).

These criteria are greatly influenced by process parameters, such as mass flow rate, velocity of the jet (hence pressure), nozzle diameter and design, stand-off-distance, feed rate and depth of cut, and the properties of the material being cut.

MACHINING CHARACTERISTICS

The results of the tests conducted confirm the following machining characteristics of WJM:

(i) The ability of the jet to cut or pierce is maximum when impinged perpendicularly onto the target material[5].

(ii) The specific energy in cutting is lower than that required for piercing. (Specific energy is the energy required to erode unit volume of work-material). This can be explained by assuming that the groove generated in cutting allows for 'counter flow' of the jet to escape freely and lessens its tendency to build a 'liquid cushion'[5].

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(iii) The opening of the groove cut or the hole pierced becomes enlarged and irregular in shape with the increase in stand-off distance (SOD). With increased SOD, the jet flares out due to peeling-off effect caused by air friction. Theoretically, any divergence causes the jet to cut less effectively and less accurately.

It is found that the MRR increases with the increase of SOD upto a certain limit, after which it remains unchanged for a certain tip distance and then falls gradually. This is explained as follows. Small MRR at low SOD is due to a reduction in nozzle pressure with decreasing distance whereas a drop in MRR at large SOD is due to a reduction in the jet velocity with increasing distance[6].

In general, the feed rate, depth of cut (hence MRR), and the quality of finish go up with increase in pressure with respect to the strength of the material[3]. Figs 1 and 2 show the variation range of groove depth and MRR with pressure for various classes of materials[5].

Investigations of Leach and Walker[4] on the jet characteristics reveal that the jet consists of a central core of main mass surrounded by a fine spray of water particles. The core is discontinuous except near the nozzle end. They further observed that the spray reduces with less nozzle pressure.

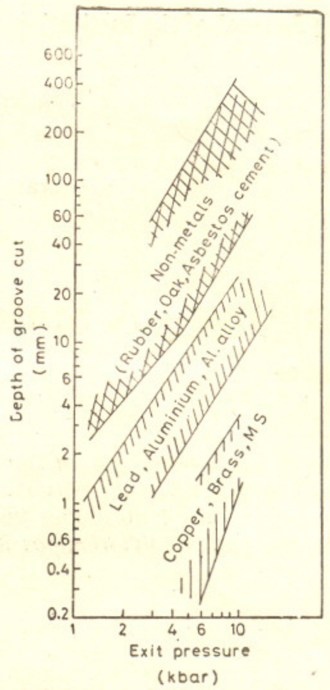

Fig 1 Grove depth at different exit pressures [5,11]

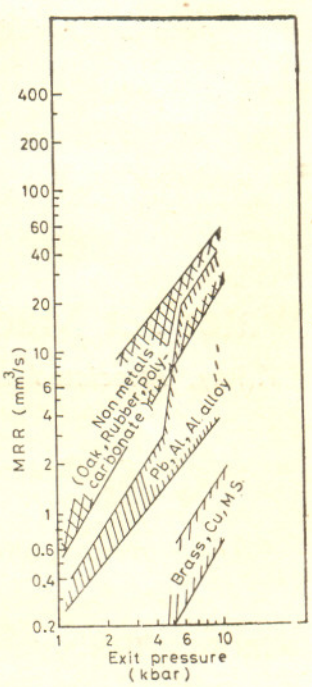

Fig 2 Material removal rate at different exit pressures [5,11]

Thus it may be concluded that the discontinuity of the jet core causes repeated impact loading on the target material. The probable explanation to better surface finish with increased pressure may be as follows. Spray and jet velocity increases with an increase in pressure. Thus, the cutting speed remaining constant, more water particles are brought into action. This phenomenon is fairly comparable to the conventional grinding process where a large number of cutting edges produces a better surface finish. However, much work is yet to be done on the degree of surface finish and the accuracy attainable by this process.

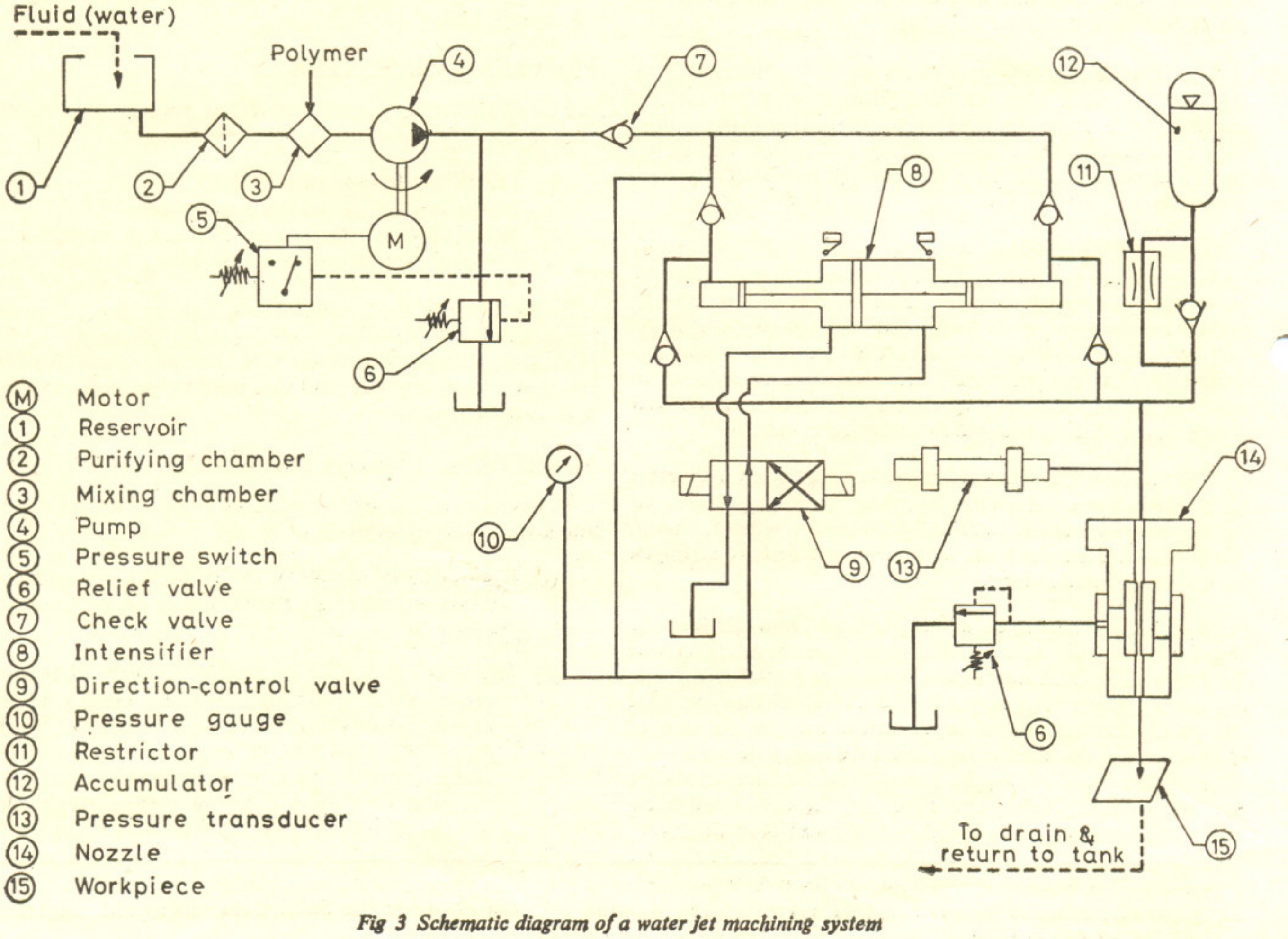

Fig 3 Schematic diagram of a water jet machining system

DISCUSSION

The elements of a jet cutting system basically consists of a high pressure source (pump) and a shaped nozzle which concentrates the liquid and forms the jet through the nozzle mouth. Other accessories include high pressure tubing and their fittings, valves, various holding fixtures, and a control panel. The last element is the drainage system which collects the water (together with fine dust like chips of the work material) after it has passed through the work-piece). A schematic diagram of the process is shown in Fig 3.

Jet cutting requires a continuous high pressure delivery and this limits the life of the components, since at high pressures fatigue failure of the mechanical components occurs. However, with improved materials, fatigue in the high pressure range is of less importance than seal life.

The compressibility of water at high pressure has to be taken into account. This means that a considerable portion of the stroke of the intensifier ram occurs before the pressure rises to the level when the outlet check valves open and the fluid is actually delivered. For continuous operation where two intensifier cylinders are used, one at each end of a central double-acting hydraulic cylinder, a considerable amount of pressure drop would occur at the nozzle during each reversal of the drive cylinder. Also, the pressure surge will induce shock load on the nozzle. To eliminate this, an accumulator may be used in the system. Alternatively, two properly sequenced intensifiers may be used with their own hydraulic drive cylinders. The sequencing can be done by electrical switches or special cams.

Plain water at room temperature freezes at a pressure around 9 kbar. Hence, for high pressure operation the working fluid is usually a 1:1 mixture of glycerine and water. (The limiting working pressure for pure glycerine is about 14 kbar). The mixing of glycerine increases viscosity, thereby minimising leakage. Also the compressibility is reduced to some extent.

Thick-walled tubes are used in high pressure systems. The ratio of inside to outside diameters is usually between 5 and 10. Tubes are made of a solid stainless steel wall or a composite wall with stainless steel inside and carbon steel as jacket (shrink fit). By using auto-frettaged tubes, fluids can be constrained at pressures greater than the yield stress of the tube material.

The nozzle is the most important and critical part of the system. The function of the nozzle is to convert high pressure liquid into a high velocity jet with minimum lateral expansion and spray; and to ensure effective cutting the jet must remain coherent over the maximum distance from the nozzle tip.

Ideally a nozzle consists of a conical entry of 6°-20° included angle followed by a cylindrical exit 2-4 times the diameter in length[4]. For quality cutting the nozzle tip diameter may be as small as 0.05 mm. Long exponentially tapered nozzles have been developed to give better results. However, these are much more complicated, difficult to manufacture and expensive.

Nozzle materials generally used are tungsten carbide, sapphire, diamond, and other alloy steels. Synthetic sapphire is most commonly used for precision cutting. This is because saphire is very strong, especially in compression, and nearly as hard as diamond; yet it can be polished to a very smooth surface by using a diamond paste. The level of turbulence at the nozzle outlet is affected by the roughness of the inside surface of the nozzle. The flow is unaffected if the roughness height is less than the thickness of laminar sublayer.

Neusen and LaBrush[7] report that the nozzle material must have a yield stress of at least 105 kgf/mm^2 and a hardness of about 400 BHN for jet velocities upto 1 220 m/sec.

The life of a nozzle varies widely and it depends on the nozzle material, the velocity of flow, and the amount of suspended particles in the working fluid (water).

Franz[8] reports improved jet coherence with the addition of a long chain polymer to the cutting fluid. Addition of such a polymer (*eg*, polyethelene oxide) to the cutting fluid increases the viscosity and virtually eliminates spray, improves cutting efficiency, and reduces wetting of the target material. Better jet coherence minimises noise also. Coherent jets of length 500-600 times the diameter can be achieved by using such additives. This means that a 0.05 mm diameter nozzle may produce a 25 mm long coherent jet while a 0.35 mm diameter nozzle may produce a 175 mm long coherent jet[6].

The advantages of WJM are:

1. Water is cheap, non-toxic, readily available, and can be disposed easily.

2. The jet approaches the ideal single point tool. This facilitates designing an efficient automated system.

3. Any contour can be cut and the process gives a clean cut. Accurate cutting enables intricate shapes including sharp corners. Further, the operation is possible in both horizontal and vertical positions.

4. The cut does not have to start from the edge, *ie*, no pilot-hole is necessary when cutting in the middle of a sheet.

5. Very narrow cuts in some materials reduces wastage and lowers cost.

6. The method does not generate heat. Hence there is no possibility of rewelding of the edges of laminations being stack-cut. (This occurs frequently in cutting plastics with conventional methods).

7. With no heat generation, there is no thermal degradation of the work-material.

8. Fire hazards are reduced; hence the process is suitable for explosive environments.

9. Blade clogging is avoided. This occurs when cutting sticky materials mechanically.

10. Less moving parts and hence less maintenance is required.

11. Cutting forces are in a single direction. Negligible lateral forces permit trimming cuts close to the edge.

12. Dustless atmosphere—this is particularly advantageous for cutting asbestos and glass fibre insulations which produce dust.

13. No pollution problem.

14. The same water can be reused after filtration. Hence only a small make up water will be necessary.

Primarily, the technical limitations of WJM are sealing against high pressure and the hardness of the work-material, the commercial limitation being the high capital cost for the equipment. However, for some non-metallic materials (where the power requirement is small), advantages of this technique are believed to exist in flexible processing and low cost of auxiliary substances[5].

The undesirable wetting of such things as paper is also a problem. However, this is not a major problem as it appears to be. High cutting speed requires a small quantity of water, most of which passes cleanly through the cut. The little heat generated in the cutting action is sufficient to evaporate the residual water thinly spread over the cut surface.

Accuracy is sometimes impaired in cutting non-homogeneous materials. The jet follows the lines of natural weakness occuring in the material, such as, a void or a soft spot can deflect the jet, causing it to wander[2]. Also, in brittle materials the stress waves may cause fracture in regions far from the impact area.

Safety against the jet is vital. However, the high system pressure is not a serious safety problem because a fractured component does not explode violently due to relatively low compressibility of liquid and the small amount of flow involved. The normal high pressure practice is followed in designing the system, and various safety interlocks and proper system venting are provided in case there be any operational defect.

COMMERCIAL APPLICATIONS AND DEVELOPMENTS

In 1971 McCartney Manufacturing Company (USA), the pioneer in commercial quality jet-cutting, produced armchair bases from 12.5 mm thick laminated paper tubes using templates. The same company now possesses an optical tracing system with multiple nozzles. Cutting speeds upto 5.1 m/min are achieved by electronic integration of *X*- and *Y*-axes speeds. Optimal tracing or numerical control allows more complicated profiles to be cut at optimum rates.

Jet cutting is particularly suitable for some difficult-to-machine materials. 25 mm aluminium honeycomb, for example, can be cut at a speed of 0.85 m/sec.

Steel and brass can also be cut by water jets. However, the high pressures needed for these are as yet beyond the range of commercially available intensifiers.

Recent developments are aimed at combining jets with mechanical methods of cutting. Here the high pressure jets produce slots and cracks which weaken the material thereby making it an easy task for the conventional cutters. In some of the oil drilling tests ESSO used conventional roller drilling bits to which jets were added. This produced a 2 to 3 fold increase in drilling speed. Six nozzles, each 3.3 mm in diameter and at 0.7-1.0 kbar pressure, were used with conventional roller drilling bits of 222 mm diameter. Japanese railway engineers increased their tunneling speeds by 2-5 times using two to four nozles, each 0.3-0.4 mm in diameter and at 4 kbar pressure with rotary percussive rock drills.

In the USA and Britain, jet cutting is now being applied in the shoe industry. The saving in sheet cutting is reported to be 5-15% as compared to the conventional methods[1].

CONCLUSION

A variety of materials can be cut by this process. Some of the materials which have been successfully cut at the British Hydromechanic Research Association (BHRA) using high pressure water jets are asbestos cement board, brake shoe material, corduroy, crepe, high density polyethelene, leather, newsprint, nylon tyre fabric, plywood, polypropylene gasket material, etc. The Japanese engineers too are doing considerable researches in this field. It is expected that a safer and more effective tool for quality cutting will emerge in the next few years with WJM opening up a new era in modern machining.

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