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A Novel Approach to Hybrid Abrasive-Cavitation Methods for Machining

Vivek Vij and Kashish Goyal

Department of Mechanical Engineering, DAV Institute of Engineering and Technology, Jalandhar, India
vivekvij296@gmail.com

ABSTRACT

The precision and accuracy of the work piece with Nano finish and surface veracity requirements has directed to a revolution in manufacturing sector. Traditional manufacturing methods utilize mechanical energy for machining and the material removal takes place by chip formation but high dimensional accuracy and surface finish cannot be obtained by non-conventional machining processes. Taking these limitations into consideration, many non-traditional machining (NTM) methods have been developed which are not dependent on shear forces for material removal. As the removal of material takes place in the form of atoms or molecules in NTM processes, thus high degree of dimensional accuracy with complex shape requirements can be obtained by these methods. In this paper, a new non-conventional machining method known as Bubble Machining is presented. Bubble machining (BM) is based on the process of cavitation. The proposed setup along with associated process parameters are discussed in the paper.

Keywords- Traditional manufacturing, Non-traditional machining, Bubble Machining, Cavitation

INTRODUCTION

Conventional machining processes are those processes in which there is a physical contact between cutting tool and workpiece and the resulting shear is responsible for removal of the material. The change in the shape of the workpiece is due to the mechanical force applied by the tool made up of harder material. Since the removal of material takes place in the form of chips in conventional processes [1], high amount of frictional force is generated leading to undesirable heat generation which further causes distortion and surface cracks [2]. Moreover, certain materials with complex shapes cannot be machined by traditional manufacturing methods. Hence to accomplish the new challenges and shape requirements with high dimensional accuracy, Non-conventional machining processes have been developed. In NTM, energy in being utilized in its direct form for machining and the material removal takes place in the form of cluster of atoms or molecules [3]. The tool and workpiece are not in direct contact with each other hence no heat is generated due to friction. As per the energy used for material removal, NTM processes can be classified into four categories: Mechanical, Thermal, Electrochemical and Chemical. Abrasive jet machining, water jet machining, ultrasonic machining, electric discharge machining, electrochemical machining, laser beam machining, electron beam machining is some of the non-conventional processes of machining. Cavitation is the phenomenon of rapid formation and collapse of bubbles in a liquid due to variation in pressure. The bubbles can be vapour or gas filled and can occur under different operating conditions. Large hydrodynamic stresses and shock waves are generated when bubbles collapse. Cavitation erosion is a common defect found in daily applications which is the dislodging of small particles from the surface of a material due to highly pressurised pulse generation due to collapsing of bubbles. It is an undesirable process as it decreases the performance of hydraulic devices.

Cavitation is known to be a harmful process hence is always avoided but the high energy shock waves, large temperature generation, and impulsive luminance in the process shows a path to the researchers where it can be made use of in various fields. Figure 1. Shows the penetration of bubbles under the workpiece with the help of abrasive particles and liquid. A workpiece can be micro dimensioned with the help of an innovative method of machining known as bubble machining. Hence this paper introduces a new machining method known as Bubble machining (BM) along with proposed set up and concerned process parameters.

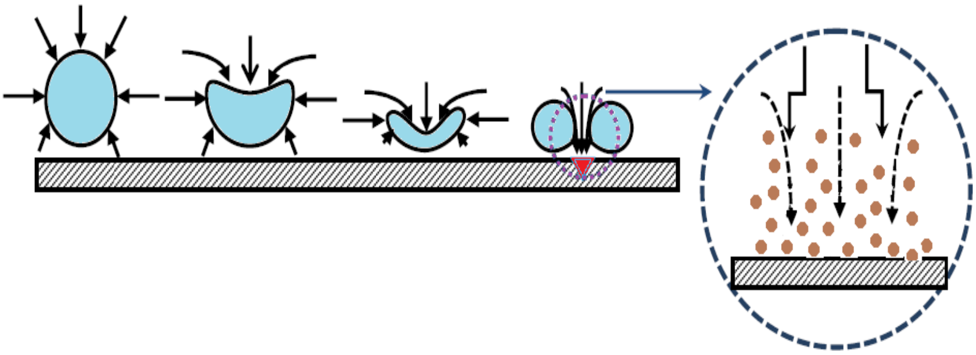

Fig. 1 Penetration of bubbles in workpiece with the help of liquid and abrasive particles

BUBBLE MACHINING

Erosion of materials due to the process of cavitation can be utilised for machining purposes as the magnitude of pressure generation due to the collapse of bubbles can be as high as 103 MPa. The rate of erosion can be increased by introducing proper ratio of abrasive particles into the liquid. The bursting of bubbles leads to the direct hammering of abrasive particles with very high energy on the workpiece thus leading to the removal of chips at micro scale. Hence the machining in this process is done at atomic or molecular level. There are various process parameters on which the rate of machining depends. Proper optimization of the process parameters must be done in order to achieve maximum rate of erosion. Moreover, the size of the bubbles generated and the amount of energy released due to their explosion also depends upon the selection of the process parameters. Figure 2 shows the ishikawa fish bone diagram presenting various process parameters [4] and the factors on which these parameters depend.

a) Cavitation Number

Cavitation number can be defined as- [$2(p-\varrho_v) / \varrho v^2$], where ϱ_v is the vapour pressure of the liquid, v is characteristic velocity, ϱ is density of liquid and p is the flow pressure.

Lesser is the cavitation number, higher would be the erosion. Pressure at upstream and downstream around the orifice is responsible for controlling this number.

b) pH of Water

Water containing certain ratio of acid results in increasing the effect of erosion on the workpiece as pH of water being used as a liquid for machining is inversely proportional to cavitation erosion. Hence pH should be less than seven.

c) Surface Tension

The occurrence of tensile forces on the surface of a liquid due to uneven force experienced by the surface particles is known as surface tension. Cavitation erosion increases with increase in surface tension hence the setup of the machine should be as to increase the surface tension.

d) Density of Energy Flux

The density of energy flux should be as high as possible as it is the energy by which the abrasive particles will hit the workpiece. More is the energy; more will be the erosion of the metal. $10mW/m^2$ is the minimum energy required to create cavitation. The density of the liquid is inversely proportional to the energy hence less dense liquid would be a prior option to enhance the rate of machining.

e) Liquid Temperature

Cavitation increases with rise in the temperature of the liquid. Hence temperature control is also an important process parameter.

f) Flow Rate

Energy by which bubbles strike the surface can be increased by increasing the flow rate of the liquid. Increase in the flow rate also leads to more cavitation erosion. The alteration in the pressure at entry and exit of the orifice results in increasing the flow rate. Moreover, variation in pressure also has inverse relation with cavitation number. More variation will lead to low cavitation number and hence higher cavitation erosion.

g) Vapour Pressure

The presence of impurities decreases the vapour pressure due to which there is decrease in the number of bubbles and ultimately the rate of erosion is reduced. Hence the liquid used for machining should be of pure form.

h) Tensile Stress

The rate of material removal can be amplified by applying tensile stress to the workpiece. With the application of tensile stresses, the rate of erosion due to cavitation in increased. These are the process parameters which affect the rate of bubble machining process. Effective optimisation of these process parameters would rise in higher rate of material removal.

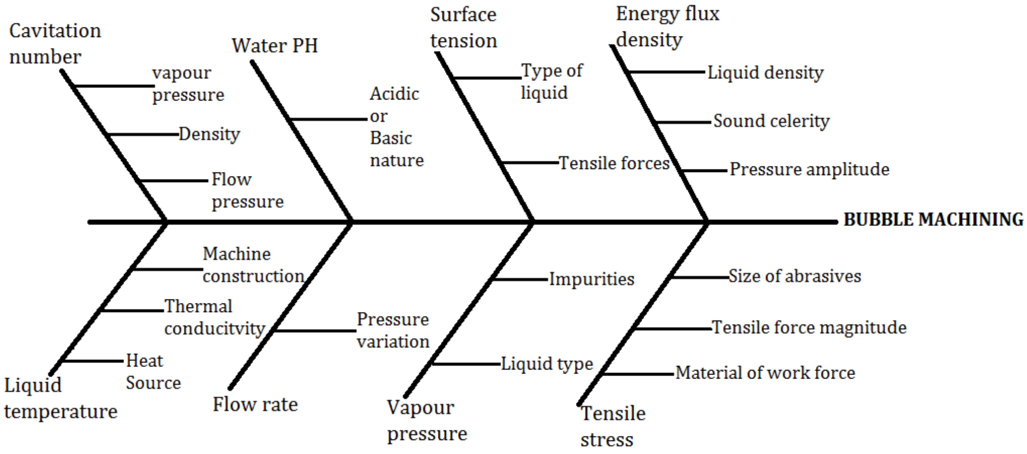

Fig. 2 Ishikawa fish bone diagram showing process parameters of Bubble Machining

PROPOSED SYSTEM

Construction

This system is based upon the fact that the shock waves which are produced by the bursting of bubbles will be helpful for machining. The system will consist of a water reservoir having a needle valve induced in it. This tank is connected to the water supply through the piping system in order to receive the water, when needed. The vacuum pump is attached to the reservoir for creating a low pressure region inside it. At the bottom of the tank a convergent nozzle is present i.e. a nozzle which is having uniformly decreasing area of cross-section made up of Stellite (material having resistance towards cavitation). The nozzle is bounded by an injecting system. Injecting system consists of the injectors which help in the continuous spraying of glycerine inside the nozzle. The bottom of the nozzle which is having a small area of cross-section is placed directly above the work piece for machining. This system also includes an auxiliary slurry delivery arrangement in which the abrasive particles are made to impinge on the work piece as shown in fig. 3.

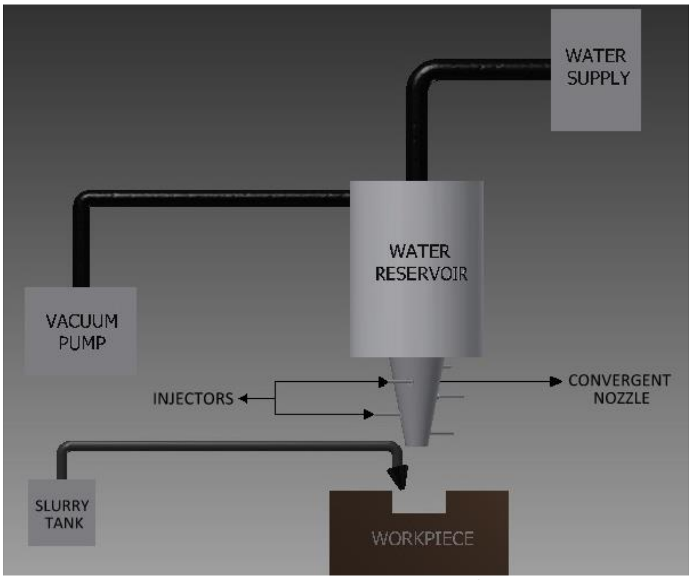

Fig. 3 The diagram depicting the proposed set up for bubble machining

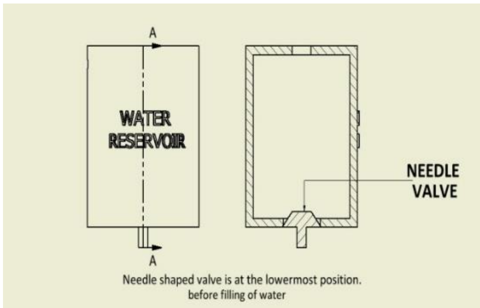

Fig. 4(a)

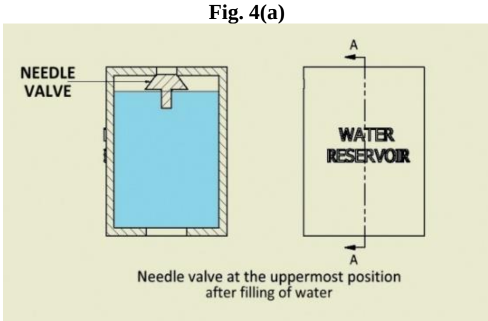

Fig. 4(b)

Working

Initially, the water reservoir is empty, when it is not connected to the water supply and the needle valve is at the lower most position as shown in the figure 4(a). When the tank is connected to the water supply, it starts getting filled with water and thus the needle valve also starts floating in the tank. As the water is continuously flowing in the tank, the needle valve starts moving upwards. When the needle valve reaches the upper most position, it hinders and finally stops the flow of water into the tank as shown in the figure 4(b). At this time the tank is filled with water and there is some vacant space above the free surface of water; now the vacuum pump which is being connected to the reservoir will start its working. The vacuum pump decreases the amount of pressure inside the chamber and thus the boiling point of the water also decreases; therefore, the water will now boil at a temperature less than 100^{O}C. If the pressure is further reduced, the boiling point of water gets reduced and a time will come when the pressure is reduced to such a limit that the water will start boiling at room temperature.

As the water starts boiling, it will result in the formation of bubbles which will help in the machining of the work piece. The bubbles along with water which are formed in the water reservoir are then made to pass through a convergent nozzle. When the valve to the convergent nozzle gets opened, the vacuum will create a low pressure region inside the nozzle which will further help in formation of more bubbles from the water coming from the water reservoir. As the bubble travels through the convergent nozzle, the size of bubble goes on increasing because the area of cross section of nozzle is decreasing uniformly and thus will result in the drop of pressure inside the nozzle. The nozzle is surrounded by the injectors, which continuously sprays the glycerine over the bubbles. The glycerine surrounds the bubble and will help in increasing the life of the bubble so that the bubble will not burst rapidly. When the bubble leaves the nozzle at low pressure and starts moving towards the workpiece, the bursting of bubble will take place. The bubble will burst because it suddenly enters into a region of high pressure after travelling from a region low pressure. The bursting of bubble will result in the formation of shock waves and these waves' strikes the work piece which will cause the material to be removed from the work piece. The shock waves produced may also provide damage to the nozzle, thus nozzle is made up of chromium nickel or Stellite as these materials are unaffected by the produced shock waves. When the large number of bubbles strikes the surface of work piece, the required amount of material can be removed from it.

The above system also includes an auxiliary slurry delivery arrangement in which the slurry of abrasive particles is made to impinge the surface of work piece. When the bubbles and abrasive particles impinge upon the surface to be machine, it results in the better material removal rate than the bubbles or abrasives alone. The bursting of bubbles will enhance the mechanical agitation of the abrasive particulates [5]. Thus, the combined effect of shock waves created by the bubbles and the mechanical agitation of abrasive particles will be helpful in removing the material from the work piece more effectively. The working of the above system can also be understood from the flow chart, given in figure 5.

Mathematical Analysis [6]

There are some equations which can be helpful in understanding the bubble dynamics. From the working it is clear that the system contains the mixture of water and bubbles. The size and the concentration of the bubbles formed play a vital role in the process of cavitation. Owing to the fact that the bubbles are low in concentration and small in size these bubbles are distributed with in the liquid and the assumption can be made that there is no relative motion between the fluid and the bubble. Whole of the mixture can be treated as a single phase and the motion of such mixture is given by single phase Euler or single phase Navier Stokes equation:

$$\rho' = (1 - \beta)\, \rho_l + \beta\, \rho_g \tag{1}$$

Where ρ' is the density of two phase mixture, ρ_l is the density of the liquid phase, ρ_g is the density of the gas and β is the fraction of void in the mixture. The density if gaseous phase can be neglected because the density of the liquid phase is much higher than the gaseous phase. The bubbles can be assumed to be spherical in shape due to its small size and thus void fraction is given as

$$\beta = 4/3\, \pi\, r^3\, n \tag{2}$$

Where n is the density of bubble population. The bubble population density keeps on changing with the growth of bubbles and due to the coalescence of bubbles. Neglecting these effects, the relation between population density and the void fraction is given as:

$$n = n_0\, (1 - \beta) \tag{3}$$

From equation (2) and (3) we have:

$$r^3\, (1 - \beta)/\beta = ¾\, \pi\, n_0 \tag{4}$$

Equations (1) and (4) constitute the continuum equation. The final continuum equation can be written as:

$$\frac{\partial p}{\partial t} + \frac{\partial(\rho v_r)}{\partial r} + 2\,\frac{\rho v_r}{r} = 0$$

Where p is the liquid pressure, ρ is the density of liquid, v_r is the radial component of the velocity and r is the radius of curvature of spherical bubble. The second equation on which the bubble dynamics work is given as momentum equation which can be formulated as:

$$\frac{\partial v_r}{\partial t} + v_r\,\frac{\partial v_r}{\partial r} = -\,\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{1}{\rho}\,(\nabla.\tau)_r$$

Here ζ is the extra stress tensor.

The bubble dynamics can be governed by considering continuum and momentum equations.

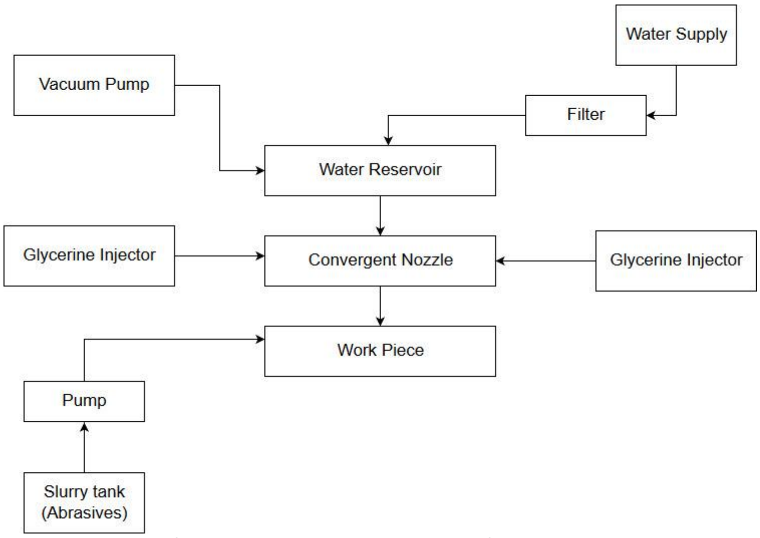

Fig. 5 The flow chart depicting the working of the proposed system

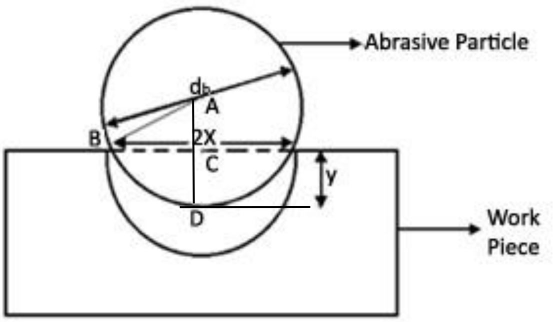

Fig. 6

Material Removal Mechanism

The resultant shockwaves which are produced by the bursting of the bubble will help in increasing the mechanical abrasion of the abrasive particles. The abrasive particles then move towards the workpiece with greater force and thus will be helpful in efficiently removing the material from the workpiece. The Fig. 6 depicts the impinging of the abrasive particles into the work piece which will help in the removal of the material.

Considering the right angled triangle ABC; we have:

$$AB^2 = BC^2 + AC^2 \quad \text{(using Pythagoras theorem)}$$

Therefore, $(db/2)^2 = X^2 + (db/2 - y)^2$

After solving the equation we have:-

$$X^2 = db\, y \qquad (\text{as } y <<<< db) \qquad (5)$$

The material removal rate per abrasive grit (Υ) is given as:

$$\Upsilon = 4/3\, \pi\, X^3$$

Therefore, from equation (5) MRR can be given as:

$$\Upsilon = 4/3\, \pi\, (db\, y)^{3/2}.$$

Advantages

- Bubble machining produces the products which are free from stresses.
- Any type of material can be machined using this method, as this method do not depends upon the electrical property of the material.
- This type of machining is highly precise and accurate [8].
- This technique uses water for machining, thus is free from any type of pollution.
- The disposal of waste is not a problem.
- The working cost of the machining is cheap.

Applications

- This type of machining can be used to give trim cuts for the assembly of the boat body.
- In the automotive sector, it helps in the machining of truck bed liners.
- Flat glass body having numerous contours can also be machined by this method.
- In the aerospace industry, it helps in the machining of the titanium bodies of the military aircrafts.

CONCLUSION

In today's world where the manufacturing or production industries are giving their best to produce the most excellent products for the consumers however at the same time causing a lot more damage to the environment; there is a need for a technique which do not causes harm to nature. Thus this technology of bubble machining is in the favour of environment as this technology do not causes any type of pollution and thus is not causing any harm to the environment. This technique uses water as cutting media which is eco-friendly; moreover, the waste water can be reutilized for the cutting purposes after its proper processing. Therefore, the above technology finds its way into the industries by giving high accuracy and precision in cutting along with eco-friendly mechanism.

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