A New Non-traditional Machining Method Using Cavitation Process

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Abstract—**The necessity of precise and accurate parts without any surface effects in different industries has led to a revolution in machining craft. Given this, non-traditional machining is widely utilized in responding to modern industrial problems. This paper presents a new method in machining of materials using cavitation process. It is called Cavitation Machining (CM). Two kinds of cavitation machining are presented: Hydrodynamic Cavitation Machining (HCM), and Ultrasonic Cavitation Machining (UCM), they will be introduced, and the parameters associated with them will be presented.**

Index Terms—**Cavitation machining, Hydrodynamic, Ultrasonic, Abrasive particle.**

I. INTRODUCTION

TRADITIONAL machining processes are kinds of machining in which the removed materials from the workpiece surface are in the form of chips. Thus, high degree of precision and accuracy cannot be achieved. Taguchi mentioned that high precision and accuracy cannot be achieved using the conventional machining processes where the material is removed in the form of chips. Moreover, the applied force can damage the workpiece surface and the attainable surface finish with the traditional machining processes is observed to be very poor [1], [2]. In many cases, the engineering materials cannot be machined by traditional machining processes because of their shape and material type and other effective factors [3]. Regarding these, non-traditional machining (NTM) processes have been developed since the World War II largely in response to new, challenging, and unusual machining and or shape requirements [4]. In NTM processes the material is removed in the form of atoms or molecules, individually or in groups. In addition, low applied forces can prevent damage to the workpiece surface, so required accuracy can be achieved by these processes [2]. NTM processes are classified into four categories according to the type of energy used in material removal: chemical, electro-chemical, mechanical and thermal [4]. Electrical discharge machining (EDM), chemical machining (CHM), electro chemical machining (ECM), ultrasonic machining (USM), laser beam machining (LBM), and abrasive/water jet machining (AWJM) are some types of NTM processes [5].

Cavitation is known as a repeated formation and violent collapse of bubbles in a liquid, which generates very large hydrodynamic stresses. These bubbles can be either gas or vapor filled and can occur in a variety of liquids under a wide range of operating conditions. The collapse of a spherical bubble causes the origin of an impacting microjet. This leads to arising local high pressures and shears. The magnitude of pressure pulse may be as high as 10^3 MPa. The implosion of the bubbles can dislodge small particles from the surface. This is called cavitation erosion. Cavitation decreases the performance of the hydraulic system, and induces noise and vibration that are undesirable [6]-[8].

Cavitation erosion is a complex phenomenon that involves the interaction of hydrodynamic, mechanical, metallurgical and chemical factors. It is a major concern in the hydropower generation industry, but cavitation has been exploited in useful spheres like, in ultrasonic cleaner, in promoting chemical reactions, and in biological and medicinal fields [8], [9].

This paper introduces a new method of non-traditional machining by using the cavitation process. This method can be called Cavitation Machining (CM). Cavitation leads to erosion in hydraulic systems. But in comparison with the time of machining processes, the time of erosion is too long. Using an appropriate proportion of abrasive particles in hydraulic liquid can reduce the time of erosion. Hence, a workpiece can be machined in a micro dimension using the Cavitation Machining (CM) process.

This paper is organized as follows. First, relevant literature on NTM processes and cavitation are reviewed. Second, the proposed methodology on the development of NTM by Cavitation Machining is presented. And finally, conclusion and future research direction are provided.

II. LITERATURE REVIEW

A. NTM processes

The difficulty in machining some new engineering materials has placed a demand for the NTM processes. The use of these NTM processes is becoming increasingly inevitable and popular on the shop floor. The demand for micro- and nano-machining has made such processes more important in the present day manufacturing environment [1].

In EDM the basic process is carried out by producing controlled electric sparks between a tool (electrode) and the workpiece, both of which are immersed in a dielectric fluid. In this process, both of tool and the workpiece should be

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conductive of electricity [10], [5].

The USM process is effectively used to machining conductive and non-conductive materials. Its material-removal mechanism includes impacting and hammering. The USM is effective and particular for all brittle materials [11], [5].

In ECM process the material dissolution occurs when the workpiece is made an anode in an electrolytic cell. The cathode tool is separated from the anode by a narrow electrolytic spacing through which electrolyte flows with high velocity. This process is for the materials which are conductive of electricity [12], [5].

In the above processes, the shape of workpiece follows of the shape of tool. There are several NTM processes as discussed in [5]. Each of NTM processes is associated with advantages and disadvantages that lead to its particular application [5].

B. Cavitation process

As frequently discussed, in cavitation process, the amplitude of pressure pulses is high (more than 1GPa), and it is also characterized by short duration (about 1 ns to μs). Because of very small dimension of implosion zones (10^{-5} m) and fast rise of pressure, the estimation of actual pressures during implosion is very difficult. Former researches show that the density of energy flux, supplied to the material by imploding cavitation bubbles in a unit of time, can be assumed proportional to the following expression:

$$J = \frac{1}{T}\frac{1}{2\rho C}\sum_{k=1}^{M} n_k\, p_k^2 \qquad (1)$$

Where T is the sampling period duration, ρ the density, C the sound celerity of liquid, M the number of pressure intervals, n_k the number of pulses measured by means of a pressure sensor in a single interval, p_k the value of pressure amplitude corresponding to each single interval midpoint, k the consecutive number of the interval [13], [14].

There are a lot of parameters affecting the erosion in cavitation. Alicja Krella [6] founded that erosion is exponentially dependent on the energy supplied to the material *(J)* by imploding cavitation bubbles; hence, every parameter affecting *J* should be considered as an important factor in cavitation erosion. These parameters and the mentioned parameters in (1) are the same. In this equation, the most important factor is density which relates to the liquid type. Cavitation erosion can increase by employing a liquid with lower density. Krella also mentioned that there is a threshold value of cavitation energy flux density—$J = 10mW/m^2$, below which no significant erosion can be identified even after 16 *h* of exposure because of the insufficient cavitation. Employing parameters should be in a way in which the amount of *J* is more than $10mW/m^2$. Another important factor is cavitation number uses in hydrodynamic cavitation (not acoustic). It can be defined as follows:

$$\sigma = \frac{p - p_v}{\rho v^2/2} \qquad (2)$$

Where p is the pressure at a reference point in the flow (upstream pressure), p_v is the vapor pressure of the liquid at the reference temperature, ρ is the liquid density and v is the characteristic velocity at the reference point.

Decreasing the cavitation number, results in higher probability in cavitation occurrence or in increase of the magnitude of the already present cavitation [15]. Bregliozzi, et al. [16], assessed steels which showed that the grain size of the steels has an important effect on the nature of erosion produced on the surface of the samples. The resistance to cavitation erosion increases continuously with decreasing grain size. These experiments showed that cavitation erosion resistance of the steel increases if there is an increase in the mechanical properties. They used water with different pH values in the experiments and observed that the erosion rate changes by varying pH value. Decreasing pH values caused an increase in cavitation damage [16]. Jazi et al. [17] considered the influence of different flow rates on cavitation. They showed that more bubbles collapse in higher flow rates, also they mentioned that cavitation bubbles occurring in higher flow rates have higher energy; hence more erosion is expected. Auret et al. [18] which used water in their experiments about cavitation showed that the erosion rate increased as a function of water temperature and it reaches a maximum amount at approximately 65ºC (for copper and aluminum). Kwok et al. [19] found this temperature about 50ºC for stainless steel. They used water in experiment to predict the erosion rate of stainless steel caused by cavitation. Erosion rate functionally increased as temperature increased from 10 to 50ºC. Yoshiro Iwai et al. [20] concluded that different surface tension of water can affect the erosion. They adjusted the value of surface tension by adding photographic wetting agent, ranging from 0.0025 to 3.0%. They saw that the erosion rate decreases gradually with addition of wetting agent. Also they observed that the size and the number of large bubble clusters reduced due to the reduction of surface tension, which is the reason why the erosive power decreases with the reduction of surface tension. Vapor pressure can affect erosion rate in cavitation. It was reported that when vapor pressure increased, the number of bubbles increases, and therefore increases the erosion rate. It can also be said that the temperature dependence of the erosion rate is due to the increase of the relative vapor pressure [21]. Takashi Naoe et al. [22] worked on the influence of tensile stress on cavitation erosion. They say that in the steady state, it is clearly recognized that the mean depth of erosion as calculated by weight loss was increased by the imposed tensile stress. The tensile stress enhances crack propagation and accelerates erosion. The amplitude of imposed tensile stress is in accordance with the range of elastic deformation. The gas (air) content in liquid also can influence on cavitation. Altering the gas content in liquid, different values of cavitation can be achieved. We can see that cavitation grows when the gas content in the liquid is increased; hence cavitation erosion can be controlled by controlling the air content in liquid [15].

III. CAVITATION MACHINING

Machining, with taking advantages of cavitation process is introduced as an innovative method of machining in micro-nano scales. By utilizing a proper ratio of abrasive particles in the conveyor liquid in this method, the possibility to increase cavitation erosion rate is achieved. Thus this method can be used in molecular and atomic scale machining. If a bubble created by the cavitation is taken as a sphere, the abrasive particles of the liquid are scattered upon the sphere's surface. Explosion of the bubbles causes the abrasive particles to thresh to the workpiece surface and, consequently, creates molecular (or atomic) chip removal from the part. For a maximum output in machining two set of parameters must be considered and controlled. First set is the ones regarding the abrasive particles. Material removal rate can be controlled with a careful selection of these parameters. The other set is those related to cavitation. These parameters must be selected carefully in order to achieve maximum cavitation and consequently maximum erosion in procedure. Moreover, proper selection of these parameters can help control the bubble's size as well as the released energy from bubble's explosion. This feature presides over the erosion of the surface.

A. Parameters associated with abrasive particles

These parameters include the particle's size, material, shape and the portion of abrasive particles in the conveyor liquid. In similar processes, aluminum oxide, boron carbide, and Silicon Carbide are utilized because of their hard substance. They can also be used in this process because the mechanism is the same. In case of shape, they must be sharp, but not spheroid, to simplify the chip removal.

B. Parameters associated with cavitation

1. Density of energy flux: the quantity of this feature can be determined from (1). This energy is interred to the abrasive particles and threshes them to the workpiece surface. The higher the energy, the more the erosion. The minimum amount of J to create cavitation is 10 mW/m^2. The amount of parameters in (1) must be carefully selected so that J reaches the maximum. Based on the equation, liquid's density has reverse relation with J. Hence, to achieve maximum erosion the liquid's density must be at minimum.

2. Cavitation number: decrease of this number results in more erosion. Thus, this number must be as low as possible. This number is controlled by means of upstream and downstream pressure around the orifice.

3. Grain size: In the case of steel, the grain size affects cavitation erosion, so that a better machining is achieved with big size grains. So if the grain size is bigger, faster machining is resulted.

4. The amount of pH in case of using water as the liquid: the more acidic water ($pH<7$) the more cavitation erosion, so an aqua with a certain portion of acid can increase pace of erosion.

5. Flow rate: increasing flow rate can increase cavitation and energy of bubbles which increase erosion. Increase of flow rate is possible by means of pressure alternation in entrance and exit of the orifice. This pressure alternation is the denominator of (2), which its increase also decreases cavitation number and consequently enhances erosion.

6. Temperature of liquid: rise of temperature to a certain rate can increase cavitation. Hence, controlling the temperature can preside over cavitation.

7. Surface tension: the power of erosion decreases in accordance with surface tension. Therefore, the setting must be helping to increase the surface tension.

8. Vapor pressure: the impure particles in the liquid decrease the vapor pressure. For example, a little salt dissolved in water can decrease vapor pressure. Decline of vapor pressure diminishes number of bubbles and consequently erosion rate falls off, so the liquid should be pure.

9. Tensile stress: applying tensile stress round the elastic deformation results in more erosion rate. More material removal rate is a result of applying tensile stress to machining part.

10. Gas content: with expansion of air in the conveyor liquid, increases cavitation for a higher rate of chip removal a certain portion of air must be mixed with the conveyor liquid and then the mixture must be entered to the system.

These ten parameters are the most effective ones in cavitation. Machining speed can be manipulated with effectual control of these factors.

Cavitation machining (CM) is administrated by two means:

1. Ultrasonic Cavitation Machining (UCM).
2. Hydrodynamic Cavitation Machining (HCM).

- Ultrasonic Cavitation Machining (UCM).

Alike the USM machine, this method can be utilized as in fig. 1. In this method, horn vibration causes local pressure decreases and creates cavitation bubbles amongst tool and the workpiece. The bubbles result in erosion by threshing the surface of the part.

Along with the mentioned parameters, amplitude and frequency of vibrations also contribute to process control. Also the distance between the tool and the workpiece must be several times the size of the abrasive particles. In this method, machining of each part is possible in a single time and the shape of machined part follows the tool's shape. This method can be used to finish the initials surface of the holes and precise parts.

- Hydrodynamic Cavitation Machining (HCM).

This method can be utilized as shown in fig. 2a, 2b. This process needs a hydraulic system to mix the liquid and abrasive particles together with proper proportion, and drives them to the orifice and to workpiece container with a certain pressure. The decrease in pressure of the workpiece container results in creating cavitation bubbles. Traveling toward the boarders, the bubbles hit the workpiece surface with the abrasive particles and remove the chip.

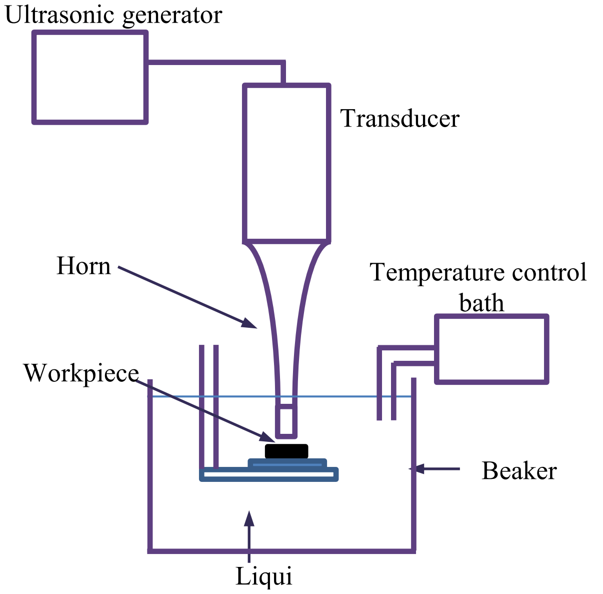
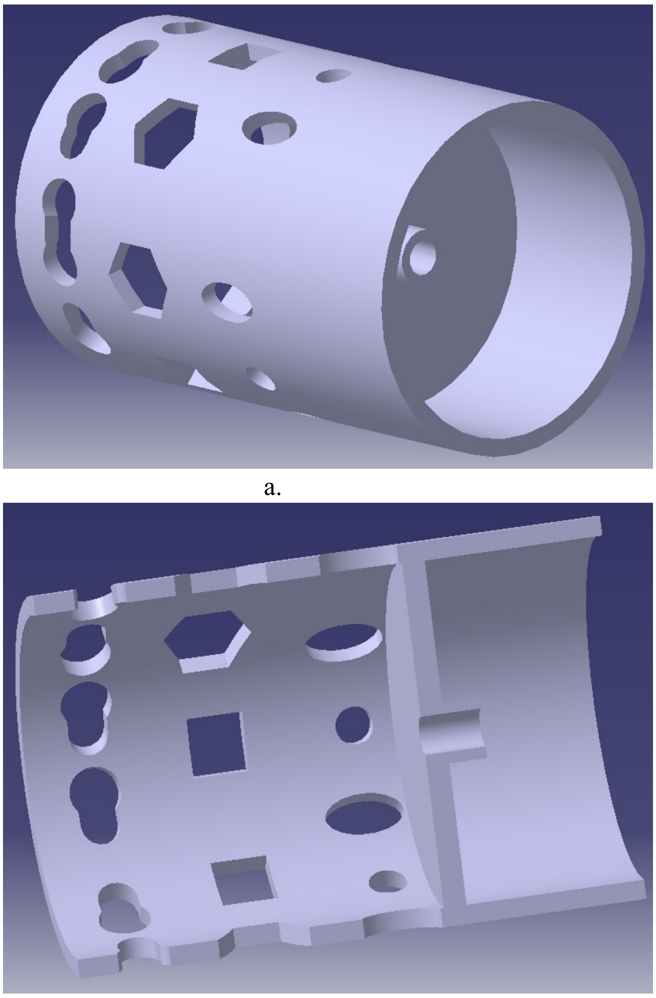


Fig. 1. Schematic of proposed Ultrasonic Cavitation Machine (UCM).

Also the conveyor liquid flows in workpiece container and drags the abrasive particles on the workpiece surface; hence, molecular (or atomic) chip removal is expected.

The significant point is that along the L (as shown in fig. 3), cavitation rate and the bubble's energy is altering, so the chip removal is also altering. In this case chip removal from the closer parts to the orifice is greater. As obvious in the fig. 2, machining several parts, concurrently, with different shapes is possible in this method. Plastic washers can be used in order to maintain the workpiece in the holes and caulking them.

Chip removal rate can be controlled, in both methods, by means of time control so that chip removal of the parts can be managed.



a.

b.

Fig. 2. (2a). Simplified Hydrodynamic Cavitation Machining (HCM) mechanisms.

(2b). cut off view of Simplified Hydrodynamic Cavitation Machining (HCM) mechanisms.

Privileges of Cavitation Machining (CM):

- Great accuracy is possible thanks to atomic chip removal.
- Concurrent machining is possible.
- Absence of residual thermal stress.
- There are no limitations of conductivity of materials, which might matter in other methods.
- Simplification of process especially the HCM process.

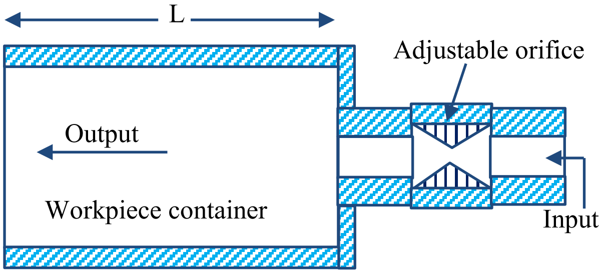


Fig. 3. Hydrodynamic Cavitation Machining System.

IV. CONCLUSION

This paper presents a novel machining method using cavitation. UCM and HCM methods were also introduced. Furthermore, the effective parameters in the pace of process were analyzed. These parameters involve: density of energy flux, cavitation number, grain size, pH amount, flow rate, liquid temperature, surface tension, vapor pressure, tensile stress, and gas content. Machining pace and chip removal rate can be controlled by means of effectual observation of these factors. This method is a functional way for machining important parts with high accuracy and precision.

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I am Mahdi Hadi born in 1988 in Isfahan (Iran). I have passed elementary and high school courses in Iran and I was always a top student in those courses. I am going to finish my bachelor of Mechanical engineering-manufacturing in Tabriz University (Iran) in summer 2011.
I think cavitation process and energy of burst bubbles could be used in different areas. So I introduced Machining process with usage of cavitation and I did some experiments which can be found in my papers (WCE-ICME195 and ICME 330).
I am willing to have cooperation with those who are interested, in order to develop this subject.

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