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# Controlled Depth Milling of Ti-6Al-4V Alloy using Non-spherical (Triangular & Trapezoidal ) Sharp edge shape ceramics abrasive particle in Abrasive Water Jet Machining

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**Abstract**— This Abrasive Water Jet Machining (AWJM) process is usually used to through cut materials which are difficult to cut by conventional machining processes. This process may also be used for controlled depth milling (CDM) of materials. This paper primarily focuses on using Non-spherical (Triangular & Trapezoidal) Sharp edge shape ceramics abrasive particle as abrasive for cutting surface material modeled is a titanium based super alloy (Ti–6Al–4V) extensively used in the aerospace industry. Also controlling the abrasive flow rate to reduce the time for machining the component. Here, an experimental setup is made with a modified attachment for abrasive feed system to machine for Ti-6Al-4V alloy. The work also investigates the surface morphology, tolerance on depth of machining and surface waviness for the modified setup. With change in mass flow rate of abrasive, the traverse speed is altered and its effects on the machining time are studied. It is observed that traverse speed is an important parameter in the case of CDM for AWJM. It is also shown that surface waviness can be reduced as traverse speed is increased by using modified abrasive feeding system.

**Index Terms**— Abrasive Water Jet Machining, Controlled Depth Milling, Non-spherical (Triangular & Trapezoidal) Sharp edge shape ceramics abrasive particle Traverse Speed, Abrasive flow rate, Surface morphology workpiece.

## 1 Introduction



Abrasive water jet machining (AWJM) is developed primarily to machine hard and difficult to machine materials such as ceramics and super alloys. It is a non-conventional machining process in which a mixture of Non-spherical (Triangular & Trapezoidal) Sharp edge shape ceramics abrasive particle as abrasive with high pressure water is converted to high velocity jet to cut various materials ranging from soft to hard like titanium, in-conel, etc. The material removal occurs due to shearing of work piece material by high velocity stream of sharp edge shape abrasive particles. The high velocity water jet creates a vacuum, which sucks the abrasives from the abrasive supply tube. Since there is no thermal and electrical energy involved in this process many materials defects are avoided. The material removal rate (MRR) is high in AWJM compared to other unconventional machining process. Miller introduce micromachining by abrasive water jet [1]. Most of the applications of AWJM are for shape cutting of different material, in the form of turning, drilling, blind pocket generation, [2] etc.

AWJM primarily depends on the following four input parameters – abrasive flow rate, traverse speed, standoff distance, and water jet pressure. Finnie [3] proposed a mathematical model for material removal by erosion of surfaces. Later, Eltobogy et al. [4] modified Finnie's model for curved surface. Chen et al. [5-6] studied striations formation due to particle distribution, dynamic characteristic and the vibration of machining system. Fowler et al. [7] were the first to introduce controlled depth milling (CDM) by studying effect of various on machining of titanium alloy. Wakuda et al. [8] identified the material response to impact of alumina ceramics in AWJM, while Chen et al. [9] optimized the AWJM process for cutting ceramics.

The abrasive water jet – controlled depth milling (AWJ-CDM) process is defined by parameters which is turn govern both, the material removal rate and surface characteristics of the milled surface. In this work, the process parameters that are controlled are pressure of jet, traverse speed, impingement angle of jet and abrasive flow rate. In the present work, pressure is controlled by variable frequency drive (VFD) and mass flow rate of abrasive particles is controlled by modified set-up of abrasive feeding system. The purpose of this exercise is to see the effect of controlled pressure and high mass flow rate of abrasive on milled surface. Most of the work reported in the literature is carried out at maximum pressure of water jet. In this work, experiments are conducted on a 5 mm thick titanium sheet under controlled pressure and abrasive flow rate. The aim of the work is to generate blind pocket of depth 0.5 mm. The morphology of impacted surfaces is compared among various combination set of input parameters. The impacted surfaces were studied with the help of Scanning Electron Microscope (SEM).

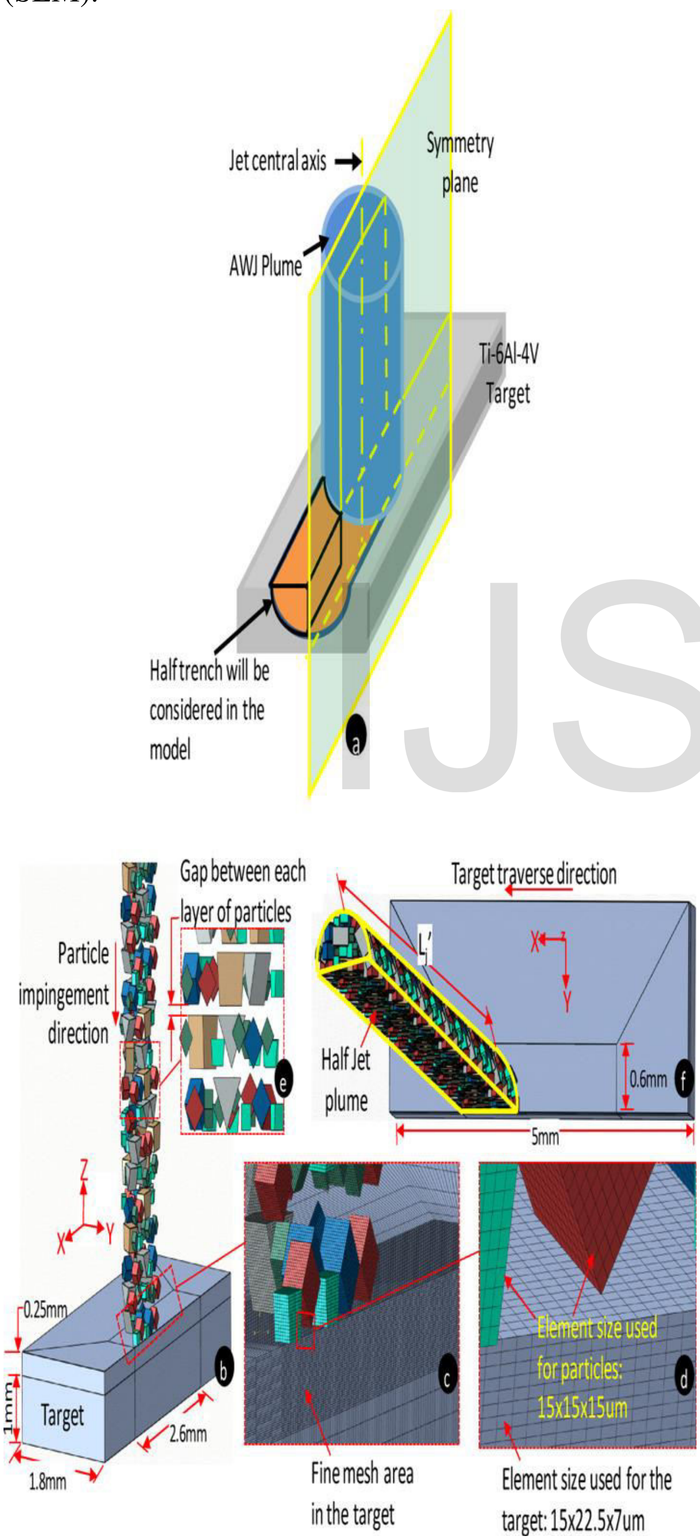
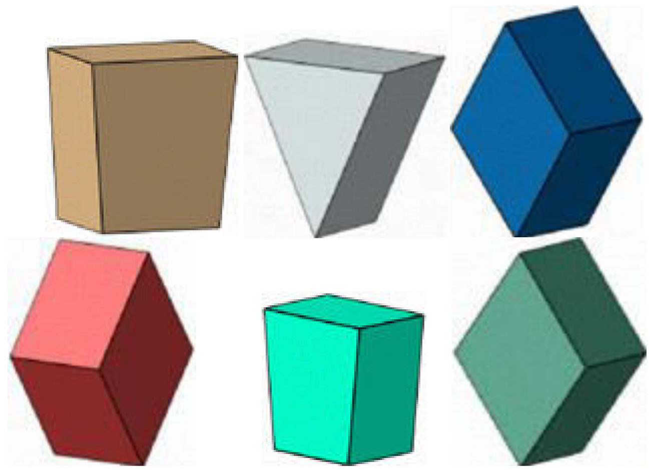



**Fig. 1 Pitorial view of process**

**Fig. 2. (a) Symmetry of the AWJ milling process at 90° incidence angle. (b) 3D view of the model. (c) Meshing of the target and the particles. (d) Zoomed-in view of the elements used in the fine mesh area. (e) Gaps among the layers of the particles; in between these gaps the target will be traversed by some percentage of total distance to be covered across the jet. (f) Tilted top view of the model showing the length of the particles column**.



Sizes and number of particles assigned to different shapes. Particles are presented in the same colour as in figure. Shapes used Assigned sizes (μm) 275 225 190 170 140 125 No. of particles of this shape in one particle mix 1 2 2 3 5 6

The paper is organized as follows: Section 2 of the manuscript explains the experimental procedure, while observations of the experiments are presented in Section 3. The results and discussions on the experiments performed are discussed in Section 4 and Section 5 highlights the concluding remarks on the work done.

## Experimental Procedure

Generation of experimental data AWJ milling trials for validating the FE model results were con-ducted on a 5-axis water jet machine (Ormond) equipped with a streamline SL-V100D ultra-high pressure pump capable of providing a maximum water pressure (P) of 413.7 MPa (60,000 psi). The jet traverse speed (Vf) can be varied in the range of 0–20,000 mm/min. An orifice diameter of 0.29 mm and focusing tube (nozzle) diameter of 1.02 mm were used throughout the experimental trials. The standoff distance (SOD), i.e. the distance between the nozzle exit and the workpiece, was set at 3 mm in all the tests. The experimental setup used during the trials is presented in Fig.2.

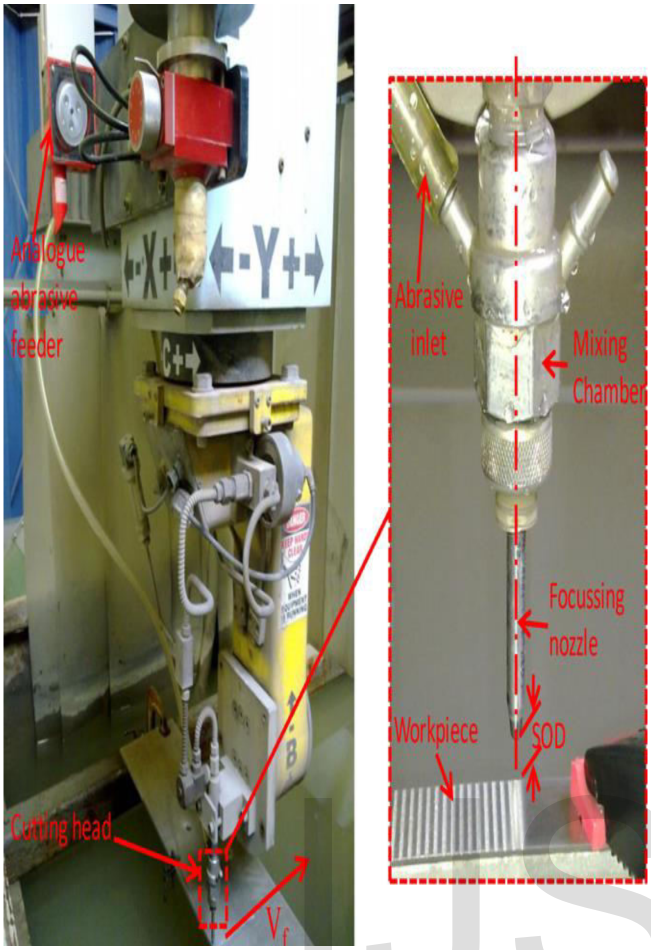



**Fig. 3 Schetematic arrangement equipment**

The experiments are conducted on a Ti-6Al-4V alloy sheet of 5 mm thickness with commercial abrasive water jet machine (OMAX C+orp.) available in the laboratory.

Table I shows the specifications of the machine. The process of AWJM is shown in Fig. 1 in which high pressure water is mixed with abrasive particles in a mixing chamber. The abrasive water jet is focussed through the focussing tube before making an impact on the selected area on the material.

***Process and result of cut on Ti6Al4V alloy***

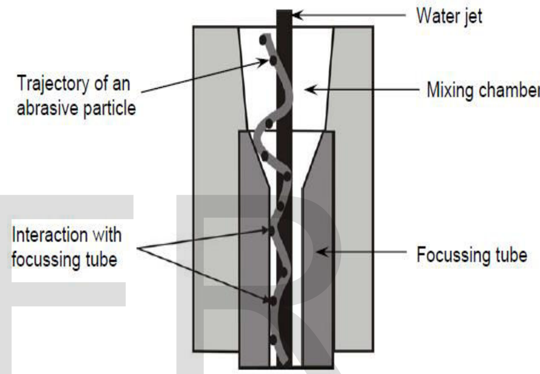



Fig. 5 Schematic of AWJM Process [10]



This work aims to achieve a blind pocket of size 50 mm x 40 mm x 0.5 mm. To hold the specimen on the machine a suitable fixture is designed. The CDM process is achieved through the etch option of the machine's proprietary software (Fig. 4). By varying the values of etch / mill depth, pockets of various depth may be created. In the given setup, the values of parameters like abrasive flow rate, pressure and stand-off distance are provided and the etch speed may be calculated automatically. Here, the etch speed was varied by controlling the abrasive flow rate. The mass flow rate of abrasive particles may be changed by changing traverse speed during the experiments. The specimen is kept under water during experimentation. All the trials are conducted at an impingement angle of $90^0$. Abrasive particles are mixed with pressurized water ahead of nozzle. The experiments are conducted at high traverse speed and large mass flow rate at low pressure of water. The pressure of the water is controlled by VFD by reducing the rpm of the motor of the pump. At various combination set of input process parameters, the morphology of the impacted surfaces is studied with the help of SEM. The modified setup used for large mass flow of abrasive particles is shown in Fig. 5. Here, a large diameter tube is connected to the existing flexible tube using reducer

**Table 1 Machine specifications**

| | |
|---|---|
| Maximum traverse speed | 4572mm/min |
| Jet impingement angle | $90^0$ |
| Orifice diameter | 0.33 mm |
| Abrasive flow rate | 0.226 kg/min |
| Mixing tube diameter | 0.762 mm |
| Mixing tube length | 101.6 mm |
| Maximum working pressure | 45 kpsi |

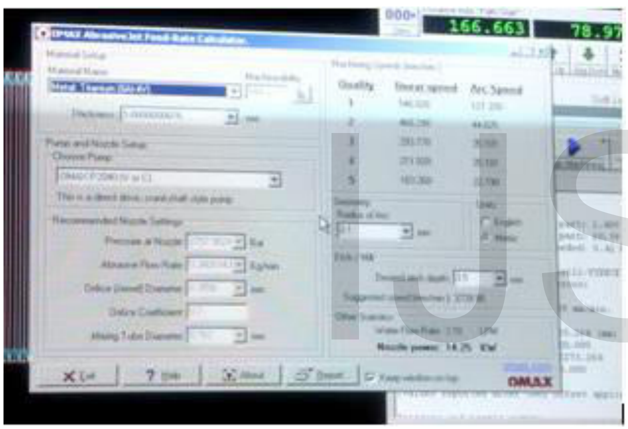


**Fig. 6 Etch option in AWJM**

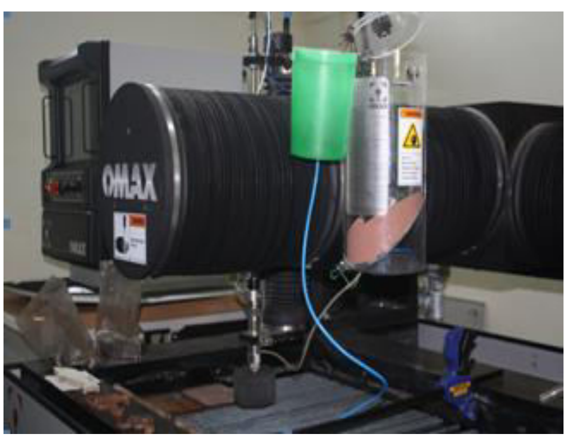



**Fig.7 Abrasive Feed System (modified setup)**

## Pressure generation system

The pressure generation system is used to deliver a constant and continuous flow of high pressure water at a prescribed value. The major drive components of the pump unit include VFD, an electric motor, the belt drive between the motor and the high pressure pump, and the crankshaft drive high-pressure pump as shown in Fig. 8.

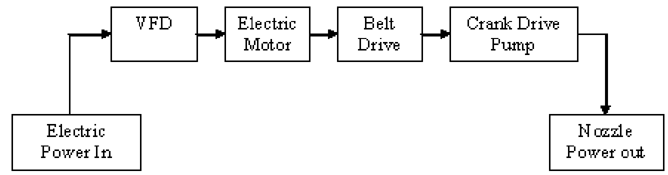



Fig. 8 System of Pressure Generation [11]

The acceleration of a given volume of pressurized water in an orifice generates high speed water jets. According to Bernoulli's law

$$P_{atm} + \frac{\rho_w}{2} v_0^2 + \rho_w g h_1 = P + \frac{\rho_w}{2} v_{pipe}^2 + \rho_w g h_2,$$ Where P is pressure, h is height and v is velocity

As here, $h_1 = h_2$, $P_{atm} << P$ and $v_0 >> v_{pipe}$, the approximate theoretical velocity of the exit water jet is

$$v_{0th} = \sqrt{\frac{2P}{\rho_w}}$$

While in practice

$$v_0 = \mu v_{0th} = \mu \sqrt{\frac{2P}{\rho_w}}$$ [11]

where, $\mu$ is an efficiency coefficient that characterizes momentum loss due to wall friction, fluid flow disturbances and the compressibility of the water.

### Abrasive feeding system

The function of the abrasive feed unit is to deliver a predetermined continuous flow of abrasive material to the jet (Fig. 6). The abrasive jet system combines high-speed flow of water with the flow of abrasives to create an abrasive jet that cuts through a wide range of materials. The abrasive is stored in a hopper on the moving head of the XY table. An air-controlled valve releases a stream of abrasive into a feed line where it flows to the nozzle. This stream causes a suction that draws the abrasive and air through the plastic feed tube. The water, abrasive and air then enter a mixing tube where they combine to form a cutting stream.

In this work, mass flow rate of abrasive particles is controlled by a modified set-up of abrasive feed system. This modified method is compared with the existing method of the abrasive feed system, with all other parameters being same. The working parameters for the two methods are shown with the help of Table 2.

**Table 2 Working Parameters**

| | *Existing setup* | *Modified setup* |
|---|---|---|
| Abrasive Flow Rate, AFR (kg/min) | 0.226 | 0.385 |
| Traverse Speed, TS (mm/min) | 2790 | 3390 |
| Pressure (Kpsi) | 45 | 31.6 |
| SOD(mm) | 0.3 | 0.3 |

## Observations

This section shows the effect of abrasive flow rate and traverse speed on surface morphology. This section presents the study of the microscopic behaviour for samples milled by using modified setup of abrasive feed system.

### Microscopic behaviour of milled surface

The appearance of the sample surfaces milled surface by AWJM is shown in Fig. 9 and Fig. 10 for the two cases of AWJ-CDM (existing and modified setup respectively). The structure of the material is observed by SEM.

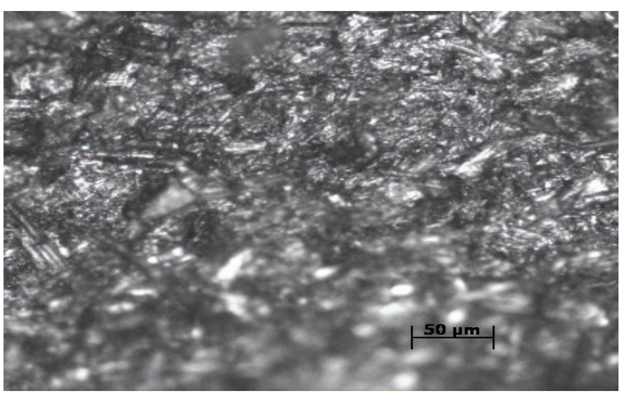



Fig. 9 Microscopic view of the milled surface for the

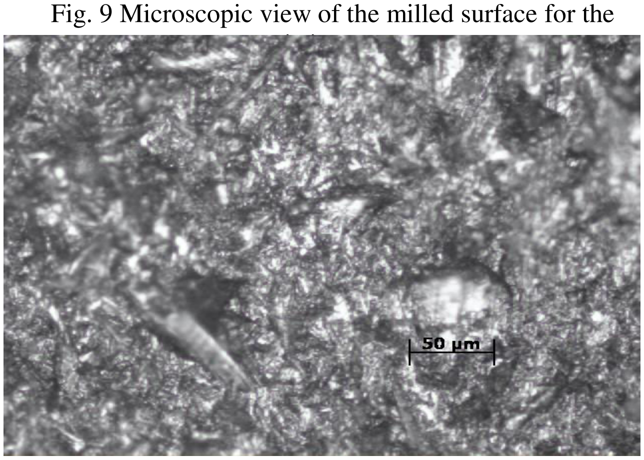



Fig. 10 Microscopic view of the milled surface for the modified setup

## Result and Discussions

Samples of Ti-6Al-4V alloy sheet are subjected to different mass flow rate of abrasive by increasing traverse speed and keeping other parameters, as shown in Table 2, constant. It can be seen in the SEM photographs that material surface morphology is almost same for two abrasive mass flow rates at two setups. The work leads to high traverse speed, with high abrasive flow rates at low pressure (31.6 Kpsi). On comparing the surface morphology as shown in Fig. 7 and Fig. 8 for the two methods of abrasive feed, it is observed that the surface roughness and waviness were with in 5% for the two experimental setups [11-12]. Depth achieved in this work is also same as in the existing setup.SEM photographs of at different magnification are studied out in this section, using this it is concluded that by using modified set up of abrasive feeding system about 20% machining time is reduced (Table 2).

## Concluding Remark

In this work, three main parameters Non-spherical (Triangular & Trapezoidal) Sharp edge shape ceramics abrasive particle as abrasive , abrasive flow rate and traverse speed were varied to study the resultant surface morphology. The basic objective was to understand whether the machining time can be reduced in case of AWJ-CDM without compromising on the quality of machined parts. It has been observed that with the modified setup of abrasive feed system, a reduction of approximately 20% time for milling the Ti-6Al-4V sample is achieved. Further, on comparing the surface morphology obtained by using the two methods of abrasive feed system in the case of AWJM, it is observed that the surface roughness and waviness were with in 5% for the two cases.

More experiments would be carried out in future to develop a mathematical model and to obtain the optimum values of traverse speed and abrasive mass flow rate for different sets of test materials

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