Theoretical and graphical analysis of abrasivewater jetturning

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ABSTRACT: *Recent developments in the materials technology, as well as the requirements for more complex and economic machining processes, demand new approaches to the machining of materials. The machining of lightweight materials, specialty metals, ceramics, and advanced metal matrix composites requires careful machining strategy to maximize performance, minimize tool wear and avoid material distortion or destruction due to thermally induced oxidation, shear stresses, thermal stresses, vibration. It will be of great importance to develop a machine tool that is less sensitive to material properties, has virtually no thermal effects, imposes minimal stresses, is free of vibrations and provides acceptable surface finish. Abrasive water jet (AWJ) technology offers the potential for the development of such a tool.An explicit finite element analysis (FEA) of a single abrasive particle impact on stainless steel in abrasive water jet (AWJ) machining. In the experimental verification, the shapes of craters on the workpiece material were observed and compared with FEA simulation results by means of crater sphericity. The influences of the impact angle and particle velocity were observed.Especially the impact angle emerged as a very suitable process parameter for experimental verification of FEA simulation, where crater sphericity was observed. Results of the FEA simulation are in good agreement with those obtained from the experimental verification. The presented workgives the basis for further FEA investigation of AWJ machining, where influences such as particles rotation and other process parameters will be observed.The objective of the present work is to develop a mathematical model, considering the variation in jet impact angle and the kerf profile, for predicting the final diameter achieved in AWJ turning process for ductile and brittle materials. Various distributions that can represent the kerf shape and the best distribution among them is identified by comparing the predicted kerf shape with the observed kerf shape. It was observed that a sine function could represent the observed kerf geometry better than exponential and cosine functions. The proposed model is validated by comparing the predicted final diameters with experimental results obtained literature.*

Keywords*:AWJ turning, Kerf, Modeling.Explicit finite elements analysis*

I. INTRODUCTION

Manufacturing industry is being ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. These trends have placed a premium in the use of new and advanced technologies for quickly turning raw materials in to usable goods; with no time being required for tooling. Abrasive water jet (AWJ) machining technology has been found to be one of the most recent developed advanced non-traditional methods used in industry for material processing with the distinct advantages of no thermal distortion; high machining versatility, high flexibility and small cutting forces. There are several distinguished advantages of AWJ technique. It is less sensitive to material properties and hence does not cause chatter, has no thermal effects, imposes minimal stresses on the work piece, and has high machining versatility and flexibility.Further, several requirements such as tight tolerances on the machined parts and effective utilization of these advanced materials motivated one to look for certain alternatives to these advanced machining processes. In conventional methods of machining, a solid tool, made of higher hardness than work piece, makes a direct contact with the work piece material. In contrast to this, unconventional methods of machining make use of different forms of energy to process the materials and do not make any direct contact with the work material. Among the several unconventional machining processes, electro-chemical machining, electro-discharge machining, ultrasonic machining, abrasive jet machining, abrasive water jet machining, chemical machining and laser beam machining are the most popular ones. Among them, abrasive water jet machining process is gaining lot of popularity due to its ability to process a range of materials in different ways. An abrasive water jet is a jet of water, which contains abrasive material. Usually the water exits a nozzle at a high speed and the abrasive material is injected into the jet stream. This process is sometimes known as entrainment in that the abrasive particles become part of the moving water much as passengers become part of a moving train. Hence as with a train the water jet becomes the moving mechanism for the particles. However high speed jet of a pre-mixture of the abrasive and the water would also be defined as an abrasive water jet The purpose of the abrasive water jet is to perform some machining or finishing operation such as cutting, boring, turning, etc.

II. HEADINGS

1.1 Introduction Manufacturing industry is being ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. These trends have placed a premium in the use of new and advanced technologies for quickly turning raw materials in to usable goods; with no time being required for tooling. Abrasive water jet (AWJ) machining technology has been found to be one of the most recent developed advanced non-traditional methods used in industry for material processing with the distinct advantages of no thermal distortion; high machining versatility, high flexibility and small cutting forces. There are several distinguished advantages of AWJ technique. It is less sensitive to material properties and hence does not cause chatter, has no thermal effects, imposes minimal stresses on the work piece, and has high machining versatility and flexibility.

1.2 Abrasive Water Jet Turnin Abrasive water jets are extensively employed for cutting of different materials such as soft and ductile materials to hard and brittle materials. It has become the state of the art in many industries such as automobile, aerospace and many consumable product making industries .Attempts made on AWJ turning include the turning of long and small diameter parts and the production of threads on difficult-to-machine materials like ceramics, composites, glass, etc.

1.3 present works The present work is to develop a mathematical model, considering the variation in jet impact angle and kerf geometry, for predicting the final diameter in AWJ TURNING process for ductile and brittle materials.

2.1 Introduction Many researchers developed a stable abrasive water jet turning process in the field of manufacturing in order to generate high quality products. However extensive works have been reported by varying different process parameters in Abrasive Water Jet Turning.This chapter highlights the literature available on abrasive water jet machining, especially focusing on abrasive water jet turning. It also gives the classification of different types of water jets and discusses the relevance of these jets for abrasive water jet turning. It also includes the description of various components of abrasive water jet machining system, the various theories proposed for explaining the mechanism of material removal in abrasive water jet machining.The water jet cutting, also called hydrodynamic machining, technology was developed in 1968 by Dr. Norman Franze, followed by the first commercial system in 1971. A breakthrough was made by adding abrasive particles to the high pressure stream of water in the early 1980s, immediately followed by the introduction of the first commercial abrasive water jet (AWJ) system in 1983.

2.2 The AWJM Process

An abrasive water jet is a jet of water that contains some abrasive material. Abrasives are particles of special materials like aluminum oxide, silicon carbide, sodium bicarbonate, dolomite and/or glass beads with varying grain sizes. Usually the water exits a nozzle at a high speed and the abrasive material is injected into the jet stream. This process is sometimes known as entrainment in that the abrasive particles become part of the moving water much as passengers become part of a moving train. The added abrasives drastically increase the range of materials that can be cut with a water jet. Materials like super alloys, ceramics, glass, and refractory material are typically machined by this process. This process aids in achieving higher traverse speeds, machining of thicker materials, and better edge quality.The abrasive water jet-cutting process is characterized by a large number of process parameters that determine the efficiency, economy and quality of the entire process. In general, the parameters in the abrasive water-jet cutting process can be divided into four categories 1. Hydraulic parameters,– Pump pressure (p)– Water-orifice diameter (do)– Water flow rate (mw)2. Mixing and acceleration parameters– Focus diameter (df)– Focus length (lf)3. Cutting parameters– Traverse rate (v)– Number of passes (np)– Standoff distance (x)– Impact angle (φ)4. Abrasive parameters– Abrasive mass flow-rate (ma)–Abrasive particle diameter (dp)– Abrasive particle size distribution (f (dp))– Abrasive particle shape– Abrasive particle hardness (Hp)

III. PROCESS PARAMETER ESTIMATION

Determining the optimal process parameters by testing/ experimentation is a time consuming and cost ineffective procedure. The knowledge of a mathematical function that relates the cutting parameters to the cutting results is necessary for a computer controlled cutting process. An important aspect is to estimate some of the most crucial output process parameters using the input parameters. One of the critical input parameters is the depth of cut (dc), which reflects the thickness of the work-piece material to be removed. Many complex mechanisms of material removal and a huge quantity of particles involved in the process produce a strongly nonlinear and stochastic behavior of the system. The generated surface depends on several machining parameters and work piece properties. Because the AWJ process is a dynamic system, the interactions of the system inputs (machining parameters and work piece properties) play an important role on process evolution.From the technological point of view, the most interesting machining parameters are the cutting head traverse rate, the water pressure, the abrasive mass flow rate and the stand-off distance between the mixing tube and the work piece. All these parameters can be controlled during AWJ machining. Other parameters, like cutting head components' geometry, abrasive properties and work piece material properties are unchanged during the process.As explained earlier by many researchers in the field of abrasive water jet turnining, much work is to be carried out to find the critical diame

3.1 Introduction: Abrasive water jet turning (AWJT) is a new process that holds promise for efficient machining of difficult to machine materials. The process uses abrasive water jet as a cutting tool that deflects from its trajectory upon interaction with the work piece. Therefore, the final work piece diameter, in addition to depth of cut, is a function of abrasive water jet, work piece and turning parameters. Here an initial attempt is made to model the AWJ turning process that is based on existing models of erosion. A new approach is to predict the process parameters in Abrasive Water Jet (AWJ) turning. The methodology involves the application of Finnie's theory of erosion for estimation of volume of material removed assuming the impact of jet on the work piece surface at an angle to account for the curvature of work piece.

3.2 Characteristics of AWJ machining: AWJ machining technology has been increasingly used since it has various distinguished advantages over other cutting processes

- ✓ No thermal damage or distortion. The heat generated is instantaneously carried away by the water. As a result, no temperature rise occurs in the work piece. This is especially useful for cutting thermal sensitive materials and other metals where excessive heat may change the properties of the material.

- ✓ Ability to produce contours. Abrasive water jets are exceptionally good at two-dimensional machining. It is possible to cut very complicated shapes or bevels of any angle in addition to three-dimensional profiling because the process is unidirectional.
- ✓ High machining versatility. An abrasive water jet can cut virtually any materials, particularly for machining many difficult-to-machine materials such as pre-hardened steels, titanium alloys, copper, brass and aluminum, brittle materials like glasses, ceramics and quartz..
- ✓ High initial capital and operating costs. For most industrial applications, the investment and operating costs are very high.
- ✓ **Low nozzle life:** The AWJ nozzle suffers from wearing by particles, which tends to produce unacceptable cut quality.
- ✓ **Low energy efficiency:** In the AWJ machining process, material removal is caused primarily by abrasives. The kinetic energy of abrasives is less than 10% of the total energy of the water stream in an AWJ system. The water stream retains a significant amount of energy until it is collected in an energy-dissipating container.
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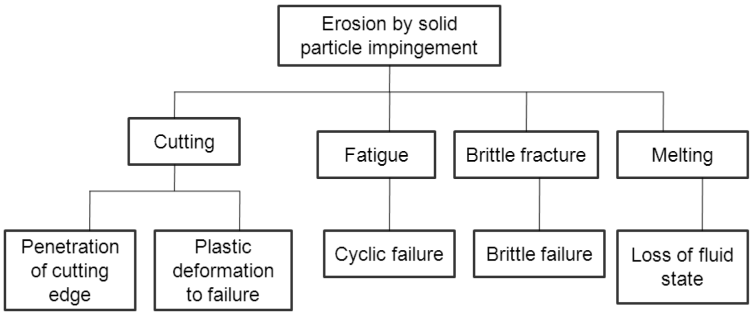
3.3 Mechanism of Material Removal in AWJ Machining. Material removal in the case of AWJs is due to the erosion caused by the impact of high velocity abrasive particles on the material. Abrasives strike the work piece at approximately one million collisions per second thus transferring a large amount of kinetic energy to the work material. The damage caused to the material by the high speed impact of particles entrained in a fluid system is called erosion.

3.4 Micro cutting mechanisms.



3.5.Abrasive Water Jet Turning .A novel turning technique that employs abrasive water jet as cutting tool was proposed [6]. Abrasive water jet turning (AWJT) is a new process that holds promise for efficient machining of difficult to machine materials. The configuration of AWJ turning is similar to that of a conventional lathe, except that an AWJ is used as a cutting tool. An AWJ is formed by mixing solid abrasive particles with high velocity water jet in a specially designed nozzle assembly. The high velocity water jet is obtained by passing water at pressure upto 380 MPa through a small sapphire orifice less than 1 mm in diameter. The abrasive particles are entrained in water downstream of the orifice with the help of a vacuum pressure that exits around the water jet. The impact of high velocity abrasive particles with the work piece causes material removal, which can generally be classified as erosive wear.

3.6 PARAMETERS INVOLVED IN AWJ CUTTING
3.6.1 Input parameters:
- Hydraulic parameters:Water jet pressure , Water jet diameter
- Target material: Fracture strength, Hardness , Ductility
- Mixing parameters: Mixing tube diameter , Mixing tube length
- Cutting parameters: Traverse speed , Standoff distance ,Angle of attack
- Abrasive parameter :Abrasive particle size ,Abrasive material ,Abrasive flow rate ,Abrasive condition (dry or slurry)

3.6.2. Output parameters:
- Kerf characteristicsSurface waviness ,Kerf width and taper ,Burr formation ,Surface finish, Depthofcut
- Geometrical and dimensional accuracy ,Material removal rate

3.7 MOTIVATION:
- ✓ AWJ TURNING is the promising method to machine hard, brittle and difficult to machine material
- ✓ Scope for optimizing the parameters to improve the process efficiency [4].
- ✓ Very few attempts to model the AWJ TURNING.
- ✓ The existing AWJ turning models [2] does not considering varying impact angle.

3.8. OBJECTIVE and SCOPE OF THE WORK: The objective of the present work is to develop a mathematical model, considering the variation in jet impact angle and kerf geometry, for predicting the final diameter in AWJ TURNING process for ductile and brittle materials. The scope of the present work is limited to the development of an approach for predicting the overall geometry of kerf and final diameter achieved while turning ductile materials using AWJ.

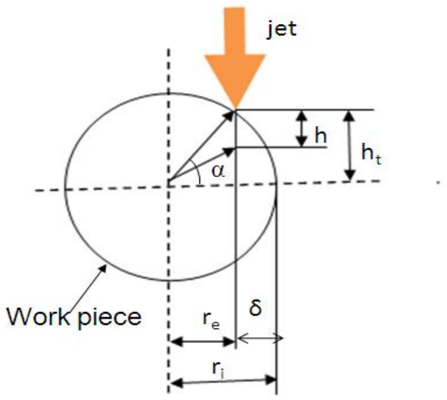
IV. INDENTATIONS AND EQUATIONS

4.2..IMPORTANCE OF MATHEMATICAL MODELING The important controlling process parameters in AWJ cutting include water pressure (P), jet traverse rate (V), abrasiveflowrate(M_f)anddiameteroffocusingnozzle(d_f). Inthisstudy,depthof cuthasbeenchosenasthemainprocess response characteristicstoinvestigatetheinfluenceof theaboveparameters.We firstdevelopa mathematicalmodelto relatetheprocesscontrolparametersto theprocessresponse characteristics. The empiricalmodel for the prediction of depth ofcutinterms ofthecontrolling parameters willbe establishedbymeansofpiecewiselinearregressionanalysis.

4.2.1 Solving Ansari and Hashish [2] model using numerical methods It was attempted in the present work to solve the existing model to obtain the final results using numerical methods through a MATLAB program. While solving that equation by using numerical methods, results of the solved equation are imaginary and do not have reasonable values. Hence, a modified approach was developed based purely on the geometry of the part to predict the final diameter of part turned using AWJ.

4.2.2 Modified approach: From the geometry

$$\cos\alpha = \left(\frac{r_i - \delta}{r}\right)$$



$$\sin\alpha = \left(\frac{h_t - h}{r}\right)$$

$$r^2 = (r_i - \delta)^2 + (h_t - h)^2$$

$$r^2 = (r_i - \delta)^2 + \left\{\left[r_i^2 - (r_i - \delta)^2\right]^{1/2} - h\right\}^2$$

$$h_t = \left(r_i^2 - (r_i - \delta)^2\right)^{1/2}$$

Fig.4.1 Work piece geometry

$$r^2 = (r_i - \delta)^2 + (h_t - h)^2$$

so,
,By solving

$$r^2 = (r_i - \delta)^2 + \left\{\left[r_i^2 - (r_i - \delta)^2\right]^{1/2} - h\right\}^2$$

$$r = \left(r_i^2 - 2hh_t + h^2\right)^{1/2}$$

Differentiating above eqn. so

$$dr = \frac{(h - h_t)}{\left(r_i^2 - 2hh_t + h^2\right)^{1/2}} dh$$

Elemental volume removal rate (from the geometry):

$$d\dot{v} = -2\pi r (dr) u$$

$$d\dot{v} = 2\pi (h_t - h) u dh$$

When solving above eqn., the result is quartic

$$Ah^4 + Bh^3 + Ch^2 + Dh + E = 0 \quad \text{(I)}$$

Where

$$A = 1 \qquad B = -\left(4h_t\right)$$

$$C = \left(4h_t^2 + r_i^2\right) \qquad D = -\left(2h_t r_i^2 + 2Kr_e\right) \qquad r_e = r_i - \delta$$

$$E = \left(3Kr_e^2 + 2Kr_e h_t\right) \qquad K = \frac{m_a v_a^2}{8\sigma\pi u}$$

4.3 MODELING OF KERF GEOMETRY. In the previous chapter, it was seen that modified approach was discarded. In order to estimate the volume of material removed, previous works (Manu & Ramesh Babu) [4] assumed kerf profile to be rectangular. Analysis of kerf profile using optical profile projector showed that this is not true. The purpose of this work is to develop an approach for predicting the overall geometry of kerf turned with AWJs. Since the geometry of kerf depends on several process parameters such as water pressure, abrasive mass flow rate and jet traverse rate, it is essential to consider all these parameters for developing suitable relations for predicting the kerf geometry.

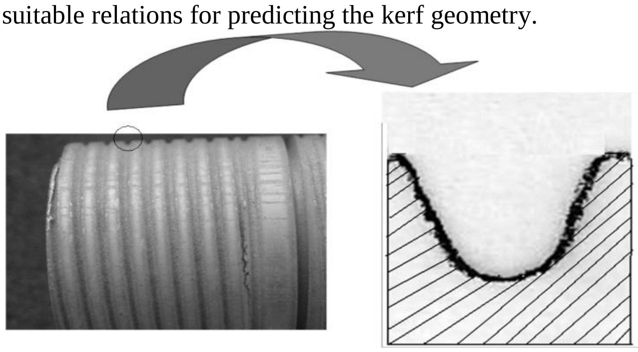


Fig. 4.3 Kerf profile got from optical profile projector

4.5 PREDICTION OF KERF PROFILE . To predict the shape of kerf produced by AWJ traversed over the work material, the proposed analysis first considers a uniform distribution of energy in the jet to predict the kerf shape and then introduces a function to obtain the kerf shape with non-uniform distribution of energy in the jet.

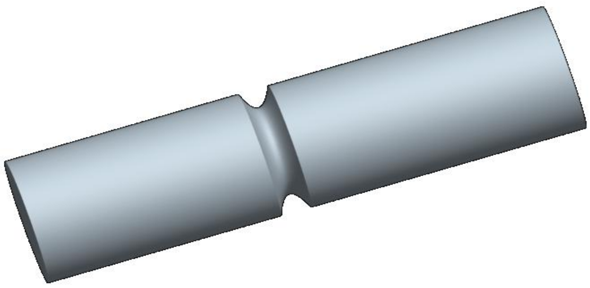


Fig. 4.4 Sschematic diagram showing the kerf formation in abrasive water jet turning

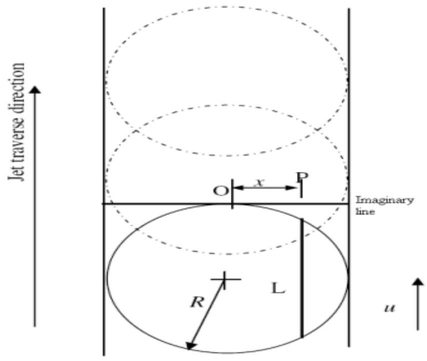


Fig. 4.5 Jet moving on imaginary line L\

4.5.1 Uniform distribution of energy: Kerf profile produced on the material with AWJ having uniform distribution of energy can be determined with the above relation. By substituting x= 0 and x = R, one can determine the maximum and minimum depth of kerf at the center and at the edges and are given by

$$h_i(0) = \frac{2k_i}{s} R \qquad (4.3)$$

$$h_i(R) = 0$$

For uniform distribution of energy across the jet, Kerf shape showing depth *hi*(*x*) at a distance x

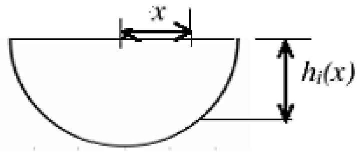


Fig. 4.6 kerf shape for uniform distribution of energy across the jet

4.5.2 Non-Uniform distribution of energy: Let the EI is the rate of energy per unit area per unit time at any radius r in the cross section of the jet. E_{max} is the maximum rate of energy per unit area per unit time in the cross section of jet. Let the variation in the energy of the jet over its cross section be represented by a function fI

$$f(r)=\frac{\dot{E}(r)}{\dot{E}_{max}} \qquad (4.4)$$

The value of fI varies from 0 to 1 from the periphery to center of the jet

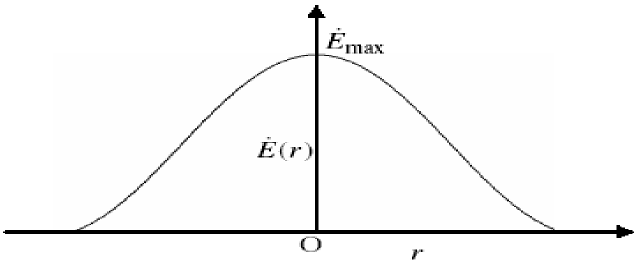
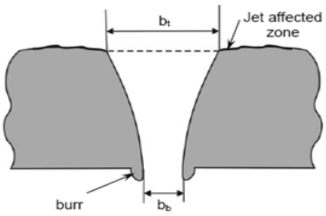


Fig. 4.7 Distribution of energy in abrasive water jet having non-uniform energy distribution

V. FIGURES AND TABLES

To develop these relations, AWJ having non-uniform energy distribution was considered. In fact, the energy distribution in the jet is non-uniform and is the resultant of the bell shaped distribution of velocity in the jet. The present work considers different non-uniform distributions while developing the relation for predicting the kerf shape produced by AWJs. By comparing the predicted shape of kerf with the shape of kerf observed from the experiments, the function that represents the distribution of energy in the jet was chosen. After identifying the distribution of energy in the jet, this particular jet produces a kerf on a particular material. The width of kerf is considered as the effective diameter of jet that interacts with material in generating kerf. This chapter covers the predicted results, discussion validation.



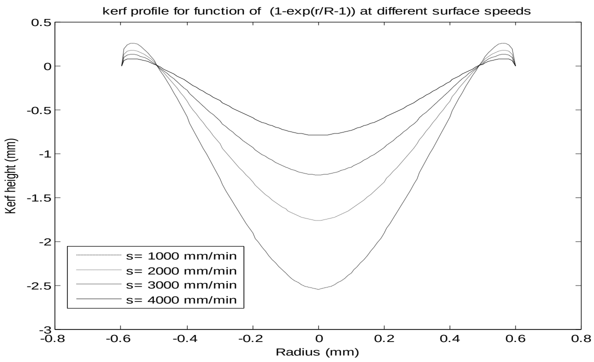
Schematic of AWJM kerf

5.2 SELECTION OF ENERGY DISTRIBUTION FUNCTION IN THE JET

Here function meansthe variation in the energy of the jet over its cross section be represented by a function f(r). To determine the function f(r), various distributions such as Gaussian, exponential, sine and cosine functions were considered to predict the kerf shape. As it is important to know the distribution of energy in the jet for developing the relations for predicting the geometry of kerf, the distribution of energy in the jet was identified by comparing the kerf observed on the material with the kerf predicted with different distributions. As explained earlier, a set of experiments were conducted to produce kerf on work material at various surface speeds, for the purpose of comparing these kerf profiles with the kerf predicted using the various functions (*f*(*r*)) like sine, cosine and exponential functions for representing the non-uniform variation of energy in the jet.The function *f*(*r*) is chosen in such a way that the predicted kerf profile is closest to observed kerf profile. The simulation experiments were conducted by varying the surface speeds 1000mm/s, 2000 mm/s, 3000 mm/s, 4000 mm/s. The different functions that were chosen to represent the energy distribution are given in table below.Profiles with the kerf predicted using the various functions (*f*(*r*)) like sine, cosine and exponential functions for representing the non-uniform variation of energy in the jet.The function *f*(*r*) is chosen in such a way that the predicted kerf profile is closest to observed kerf profile. The simulation experiments were conducted by varying the surface speeds 1000mm/s, 2000 mm/s, 3000 mm/s, 4000 mm/s. The different functions that were chosen to represent the energy distribution are given in table below

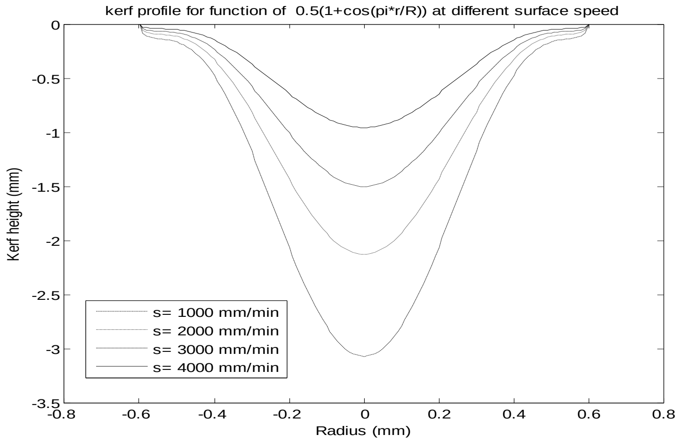
Distribution	**Function f(r)**
Sine	(1-sin(πr/2R))
Exponential	(1-exp((r/R)-1))
Cosine	0.5* (1+cos (πr/R)

.By substituting the above functions in equation (3.16) and then integrating that equation, the height of kerf at any point on the kerf can be determined. A MATLAB program was written for predicting the kerf profile and finding the area under the kerf for each function.



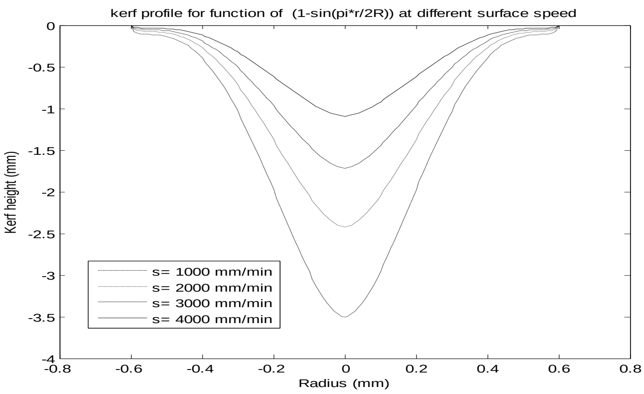
$$\left(1-e^{((r/R)-1)}\right)$$

the kerf profile generated using exponential function $\left(1-e^{((r/R)-1)}\right)$ It can be seen that in some region the profile depth is taking a positive depth, whereas the kerf profile depth must be negative



$$0.5\times\left(1+\cos\left(\pi r/R\right)\right)$$

Profile comparison for function at different traverse rate presented the profiles obtained using cosine and sine functions respectively. It can be seen that profiles are similar to observed kef profiles. Here also max. depth of kerf decrease with increase in surface speed. Profile shown in Figs 5.2, 5.3 and 5.4 satisfy the boundary condition i.e at the centre of the jet (radius =0) kerf height is maximum and at the extreme ends of the jet (radius =R and radius = -R) kerf height is zero.



$$\left(1-\sin\left(\pi r/2R\right)\right)$$

Fig. 5.4 Profile comparison for function $\left(1-\sin\left(\pi r/2R\right)\right)$ at different traverse rate

Fig.5.5 Profile comparison for 3 functions

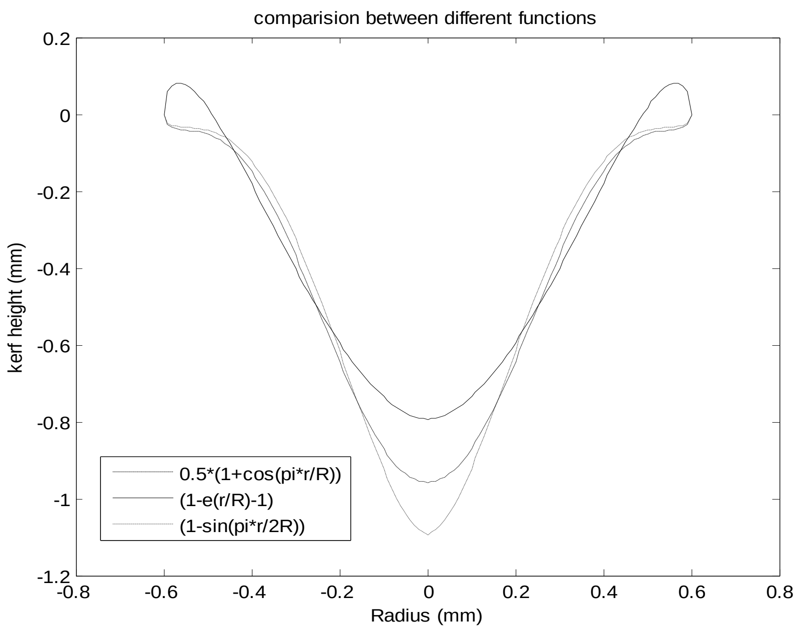


Fig. 5.5 presented the comparison of the 3 profiles obtained using 3 different distribution functions. In order to selected the most suitable one to represent the actual kerf profile , the area under each profile is compared with the actual area of the kerf. Here the atual area of the kerf is taken from the 'kerf shape drawn with optical profile projector'. That profile is redrawn on graph paper and the area obtained by counting the no. of units inside the kerf. Where as area for the particular function is obtained directly from the MATLAB program.

	Functions			
Surface speed (mm/min)	**0.5*(1+ cos(□r/R))**	**1-sin(□r/2*R))**	**1-e$^{((r/R)-1)}$**	**Actual**
s = 4000	0.5152	0.5166	0.4512	0.5600
s = 3000	0.8082	0.8104	0.7078	0.9220
s = 2000	1.1444	1.1482	1.0102	1.1684
s = 1000	1.6532	1.6576	1.4478	1.6320

Table 5.2 Comparison of kerf area in mm^2

From the table 4.2 it can be seen that sine function is closest to actual area of the kerf. So the sine function is considered as energy distribution function in the jet. By substituting the sine function in eqn. (3.16). Final equation for the Kerf profile depth at any distance x from the center of kerf is obtained as

$$h(x)= \frac{\pi}{R^2(\pi^2-8)} 0.5\times M v_a^2 \frac{1}{\varepsilon s} * f(\theta) \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} \left(1-\sin\left(\pi\sqrt{(x^2+y^2)}\Big/2R\right)\right)dy \qquad (5.1)$$

Table 5.3 Error unpredicted kerf area for selected function

	Functions		
Surface speed (mm/min)	**1-sin(□r/2*R))**	**Actual**	**Error (%)**
s = 4000	0.5166	0.5600	-7.75
s = 3000	0.8104	0.9220	-12.104
s = 2000	1.1482	1.1684	-1.73
s = 1000	1.6576	1.6320	1.57

VI. CONCLUSION

- ✓ In the present work, a new approach to predict the kerf geometry in Abrasive Water Jet Turning has been developed.
- ✓ The nature of interaction of jet with material and the material removal from part surface could be represented using Finnie's theory of erosion.
- ✓ The energy distribution in the jet has been used as the basis for predicting the kerf geometry.
- ✓ Among the various distributions considered, the sine function was found to represent the variation of energy in the abrasive water jet very well, predicting the kerf shape close to the observed shape.
- ✓ The predicted maximum depth of kerf was in turn used to estimate the final diameter of turned part under various process parameter combinations.
- ✓ The final diameters predicted using this approach were in agreement (R^2 = 0.94) with experimental results from literature.

FUTURE WORK

- ✓ Modification of the developed model employing other theories of erosion
- ✓ Employing other functions for representing kerf profile
- ✓ Modeling of AWJT of brittle materials.
- ✓ Modeling of AWJT using FEM.

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