MODELLING OF ABRASIVE FLOW MACHINING

A thesis Submitted in partial fulfilment of the requirements for the award of the degree of

Bachelor of Technology
In
Mechanical Engineering
(Production Engineering)
By

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Under the guidance of

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CERTIFICATE

This is to certify that the thesis entitled — **Modelling of Abrasive Flow Machining** submitted to the National Institute of Technology, Rourkela (Deemed University) by **Ansuman Dutta Pal** bearing **Roll No. 111ME0325** for the award of the Degree of **Bachelor of Technology** in

Mechanical Engineering with specialization in—**Production Engineering** is a record of research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the degree of Master of technology in accordance with regulations of the Institute

Place: Rourkela

Date

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I express my deep sense of gratitude and indebtedness to my thesis supervisor Dr. K. P. Maity, Professor of Mechanical Engineering for providing precious guidance, inspiring discussions and constant supervision throughout the course of this work. His timely help, constructive criticism, and conscientious efforts made it possible to present the work contained in this thesis.

I express my sincere thanks to Mr. Swarup Raj Jena, B.tech and Ansul, B.Tech for their support during the project work. I am also thankful to all the staff members of the department of Mechanical Engineering and to all my well-wishers for their inspiration and help. I am also thankful to my Friends and pals for their help during my project work.

I feel pleased and privileged to fulfil my parent’s ambition and I am greatly indebted to them for bearing the inconvenience during my B Tech. course.

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ABSTRACT

This report deals in an innovative modelling of abrasive flow machining process and simulation of the problem is done with CFD. High surface Finishing is achieved through Abrasive flow machining (AFM) process. In my project, a 2 D ANSYS assisted design is made to verify the axial and radial stress during the machining process. An already derived formulation for metal removal has been modified as per given conditions and assumptions to derive a new formula for the same. A new theoretical approach has been proposed in the current work with limitations of its own. Finally the model has been analyzed in ANSYS to compare with a previously done work, and the results verified that the current work is going in right direction. The MRR and surface removal were calculated for Titanium work piece with an industrial grade abrasive media with aluminum oxide as abrasive

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SEGMENT 1

Introduction of Abrasive Flow Machining

Exactness and Ultra finishing system identifies with a segregating and luxurious time of the general creation process. Gathering of precision parts embodies a period of last finishing operation. It is for the most part wild, work heightened and as regularly as could be expected under the circumstances incorporates a sensible bit of the total amassing cost. The valuable properties, for instance, wear resistance and power incident on account of crushing are affected by surface resistance of the facilitating parts [3].

Abrasive finishing methods are created to mitigate problems like work cost, in accessibility to obtain high surface finish. Abrasive finishing method is passed on with broad number of bleeding edges which have dubious presentation and geometry. Abrasive fine process are regularly used due to their capacity of finishing distinctive geometries of structure (i.e. Level, round et cetera.) with desired dimensional correctness and surface finishing [1,6].

1.1 TRADITIONAL FINISHING PROCESS:

Before talking about cutting edge finishing methodology, it is advantageous to comprehend the MRR that we get normally during other machining and finishing. Grinding, sharpening, micro honing are the samples of conventional abrasive finishing methodology. Multi point cutting tools as abrasive cutting particles are utilized as a part of these Method.

In all these finishing process the molecule work piece collaboration includes one or a greater amount of the essential MRR that is cutting, ploughing, grinding. Fundamentally cutting is a slicing procedure, ploughing means to dig a little and making a furrow and grinding turning into dust. The force of material distortion and change in surface harshness relies on the sufficiency of strengths and the quantity of dynamic abrasive cutting edges in abrasive finishing methodology [3].

In the process of grinding a large wheel is made up of abrasives. Grinding is more powerful in removing material than finishing surfaces because of irregular conveyance of abrasive particles. Finishing of complex parts is troublesome and obliges lavish formed granulating wheel.

In lapping process the surfaces are smoothly created and more precise than delivered in the pounding procedure. Free abrasive slurry is utilized between the work piece and the crevice. Lapping is utilized at low scraping weight and a moderate development of lap builds the surface completion and the dimensional exactness is achieved. The states of the surfaces by and large worked in lapping are constrained to rudimentary structures, for example, round and hollow and plane.

Honing is a smoothening process than removal of material process. This process works generally on low pressure, low cutting velocity, and large contact area. An abrasive made solid tool is utilized in this process. The tool rotates inside the work piece with very low reciprocating motion. Thus scratch is produced in this process [5].

Super-finishing process has a low velocity method of abrasion. The stick used in the process is made up of very fine abrasives. It is held by a holder mounted with a spring to give light pressure which is applied on work piece. Feed is given to the work piece and reciprocating motion is given to the tool [6].

1.2 Advanced abrasive finishing process:

Nano or micro level finishing need expensive methods and equipment because the traditional process of finishing can’t handle the intricacies and meet the finishing level and also traditional methods are time consuming.

That’s why, the presently it is met by new abrasive processes. AFM is one of them.it has extensive usage. MAF, MFP ad MRF are also some of the process which need not be discussed.

1.3 Abrasive Flow Machining Process (AFM):

This process utilizes a technique in which the tool is a self-formed and is able to reach the contours that are inaccessible generally. AFM technique is used for surface finishing, edge contouring, deburring and surface finishing. It is capable of super finishing areas which are not easy to reach by traditional methods by mixing the abrasives with polymer of special rheological properties. AFM produces repeatable, uniform and predictable results on many finishing operation. Normally the properties of the media in Abrasive Flow Machining process play an important role. It is non sticky. It also should have visco-elastic properties. Aluminum Oxide, Boron Carbide, Silicon Carbide, Carbine and Diamond are generally used as abrasive grains in this process [6].

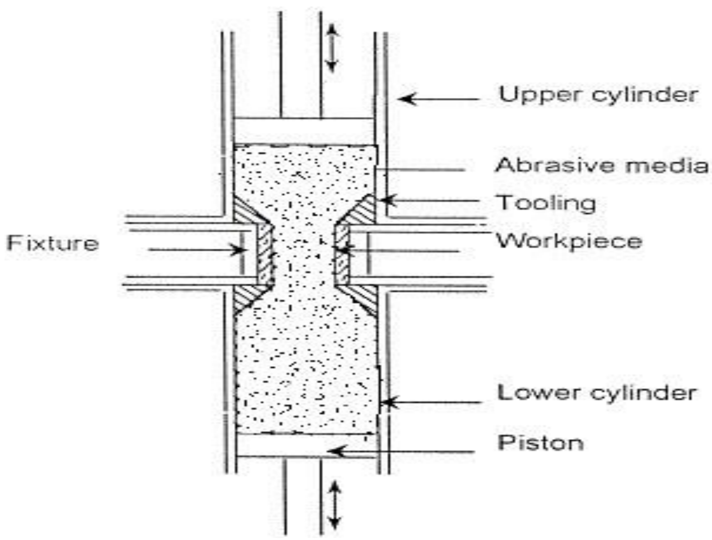


Figure No. 1: Abrasive Flow machining parts [5]

1.3.1 Working principle:

A visco-elastic polymer based material is mixed with abrasive particle and additives which is known as medium, which is generally pushed into the work-piece and depending upon setup of the instrument it may be pushed in one pass or multi pass. The medium smoothens the work piece while travelling through it. Tooling and fixture should be carefully designed

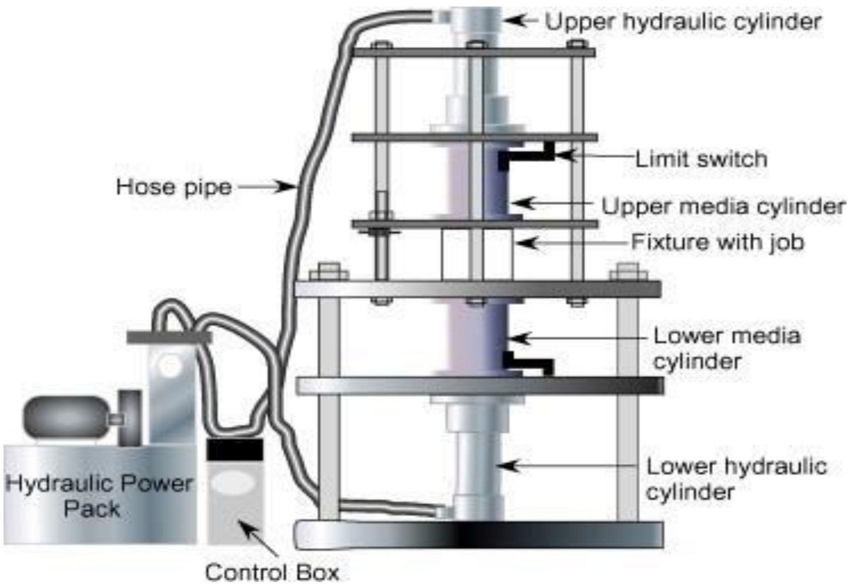


Figure No. 2: Schematic diagram of AFM [17]

Factors affecting this process are pressure, No. of cycles, initial roughness and viscosity. When proper force is applied the medium with visco-elastic properties moves in that direction with axial velocity and applies axial force .Radial force due to pressure is responsible for indentation and axial for ploughing.

1.3.2 Abrasive Flow Machining System:

AFM system consists of three different elements i.e. Machining, Tool and Medium.

Machining: The size and design of Abrasive flow machine.

Tool: locating and holding devices.

Medium: polymer based high viscous medium to hold abrasives.

Using all three factors we are able to control the generated surface

1.3.3 Features of AFM:

- Abrasion takes place only through the restricted passage for flow.
- Deburring and polishing any inaccessible and complex areas is done by the media.
- Precision of surface finish, consistency of surface and flexibility to a wide range of applications are some properties of AFM.
- High level of accuracy is achieved.

1.3.4 Application of AFM :

Figure No. 3: AFM of some complex holes [3]

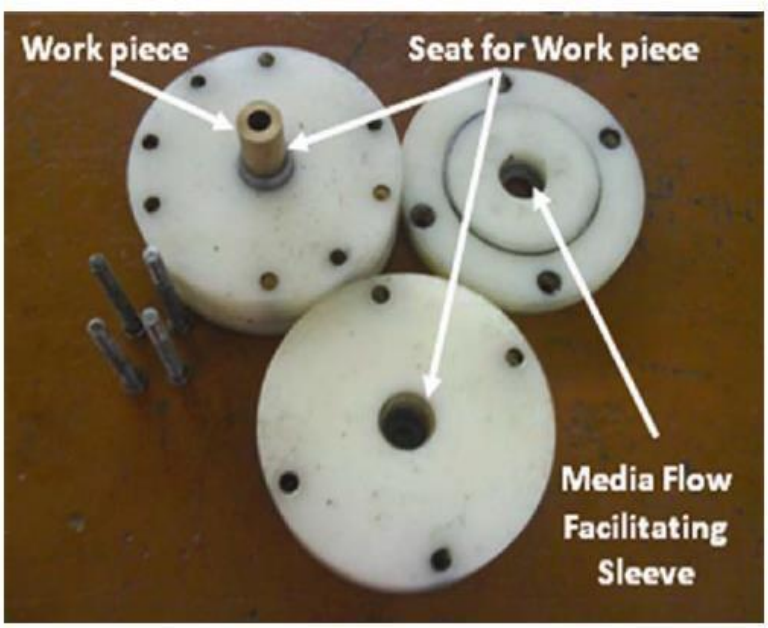


Figure No. 4: Tooling for AFM [2]

Segment 2

Literature Review

2.1 AFM process mechanism:

Rhodes [11-14] discovered quoted that viscosity of medium has a main part in finishing. The pattern of flow affecting the finish characteristics depends mainly on medium formulation, settings of machine and configuration of tool. In the restricted passage, there is increase in viscosity of medium temporarily which gives nearly pure extrusion of the medium. High viscosity medium was recommended for abrading walls of greater cross section and for radiusing edges, low viscosity medium.

Experimental investigation by Przyklenk [15] suggests that, the MRR capacity of a medium with more viscosity is 300 times more than a lower one. The important factors that affect mrr and velocity of medium- abrasive loading, their size and medium viscosity.

Rajurker and Williams [16-21] performed additional experiments to know the effect of viscosity of medium and pressure of extrusion on MRR and surface finish. Loveless et.al [20] reached a conclusion through their experiments that surface finish improvements are also influenced by initial surface roughness and viscosity.

2.2 Surface finish and material removal mechanism:

Rhodes [11-14] studied the fundamental guidelines of this process and clearly noted down the variables that control the process. He proposed that upon forcing of the medium into restricted area viscosity of the medium increases. The efficiency of abrasion while AFM depends on tooling and fixtures. Increase in volume of medium results in more interaction between the abrasives and the work piece; hence more abrasion per cycle takes place. Slow medium flow rates are preferred for uniform finishing and small radius of edges, while high flow rate results in large radii. Low viscosity medium is to be used to get better results rather than high viscosity medium. Medium flow rate depends on size and number of passage to be processed.

Perry [35] got principle and industrial usages of the AFM, i.e. precision deburring, edge contouring, surface finish and removal of layers. William and Rajurker [17-19] used a factorial approach for research to calculate the effect of medium pressure and viscosity and MRR and surface finish. Metal removal plots show that the viscosity effect was profound while the pressure effect is not so much. Jainet.al. [3-4] showed that the material removal during the AFM process is affected by the surface roughness during the start of process and hardness of the work piece. In case of softer metal, change in roughness and Material removal were found to be more as compared to harder metal. With Increase in abrasive loading MRR rate increases. It was determined out of all the parameters, the leading parameter is abrasive concentration and then abrasive size and next number of cycles that affect the most.

Fletcher and Davis [22] showed the dependency between number of cycles, pressure drop, temperature, and the abrasive concentration used. Lowering of value of viscosity and increase in medium flow rate is observed by an increase in temperature results. Change in viscosity occurs with increase in finishing time which increases the media temp. This is caused by internal shearing.

2.3 Medium composition and its rheology:

The medium is an important part of the AFM process and is able to precisely abrade the selected areas as it flows along. It is made up of a base carrier, abrasive particle and additives [24] .Base has molecular weight and has low viscosity and elastic properties. The softeners have low molecular weight and can be easily diffused in base polymer upon mixing [26-29]. Polymer matrix in this case holds the abrasive particles.

2.4 Active Grains:

Rajurkar and William [17-21] proposed, the number can be achieved by using the pseudo-frequency surface profile that is generated by the root of the data dependent system. Jain [18] found the no of active grain per unit volume by counting the number of shining grains over the medium surface. It described that by increasing abrasive mesh size and concentration the number increase.

2.5 Limitation of AFM:

- Low finishing rate.
- With time, the medium’s rheological properties degrade, and the finishing ability reduces with time.
- The abrasives in the medium don’t take part in abrasion as reshuffling does not take place.
- Complex tools need to be used in industry purpose AFM setups.
- In spiral case low force is imparted while indentation.

2.6 Objective of the present work:

The present work focus on finishing of homogenous Titanium material. The main objective of the thesis is as follows.

- Formulation of forces developed on the walls theoretically.
- Giving a theoretical model of AFM by taking suitable assumptions.
- Developing a CFD model of the AFM process with proper boundary conditions in the titanium tapered work piece.
- Calculate the material removal rate.

SEGMENT 3

CFD Modelling of AFM

To find outputs in the above mentioned AFM process we need to conduct experiments. But this is time taking and too expensive as we have to run multiple tests on multiple samples to get many results, so it is difficult to get the optimum input parameter for better result.

So the simulation of AFM is done numerically by using the software CFD (FLUENT) of ANSYS15. Then we get the desired outputs out of the simulation.

3.1 What is fluid dynamics computing (CFD):

CFD, generally abbreviated as CFD. It is the augmentation of mechanics of fluid that utilizes different numerical methods and large amount of iterative calculations to handle and examine issues that involve flow of fluid. Processors are used to do the tallies essential to reproduce the interaction between liquids and gasses when they are given a set of conditions. Fast main frame computers produce results faster.

3.1.1 Discretization Methods in CFD:

Mainly three types of discretization methods are used. The details of which are not very important. But knowing is good for future use. They are:

- Finite volume method.
- Finite element method.
- Finite difference method.

3.2.1 Applications of work piece used

Here a tapered pipe is taken for the simulation. It is used to join pipes or tube sections on same axis and provide in line conical transition.

Fig. 5 Tapered pipes

Source: (www.pipingstudy.com/reducer.html)

Some applications of the pipes are:

- Help in transporting slurries or abrasive liquids.
- Useful in services where cavitation is present.
- Used in discharge of pump.
- Used in chemical industries, in thermal equipment's, mining processes.

3.2.2 Geometry of work piece with fixture

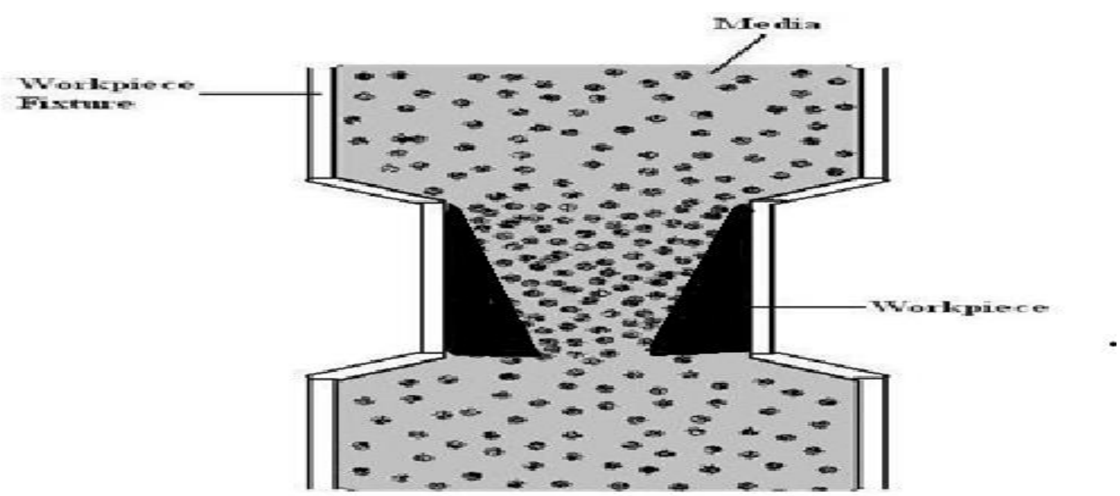


Fig. 6 Work piece with fixture

3.2.3 Design of work piece with fixture in ANSYS

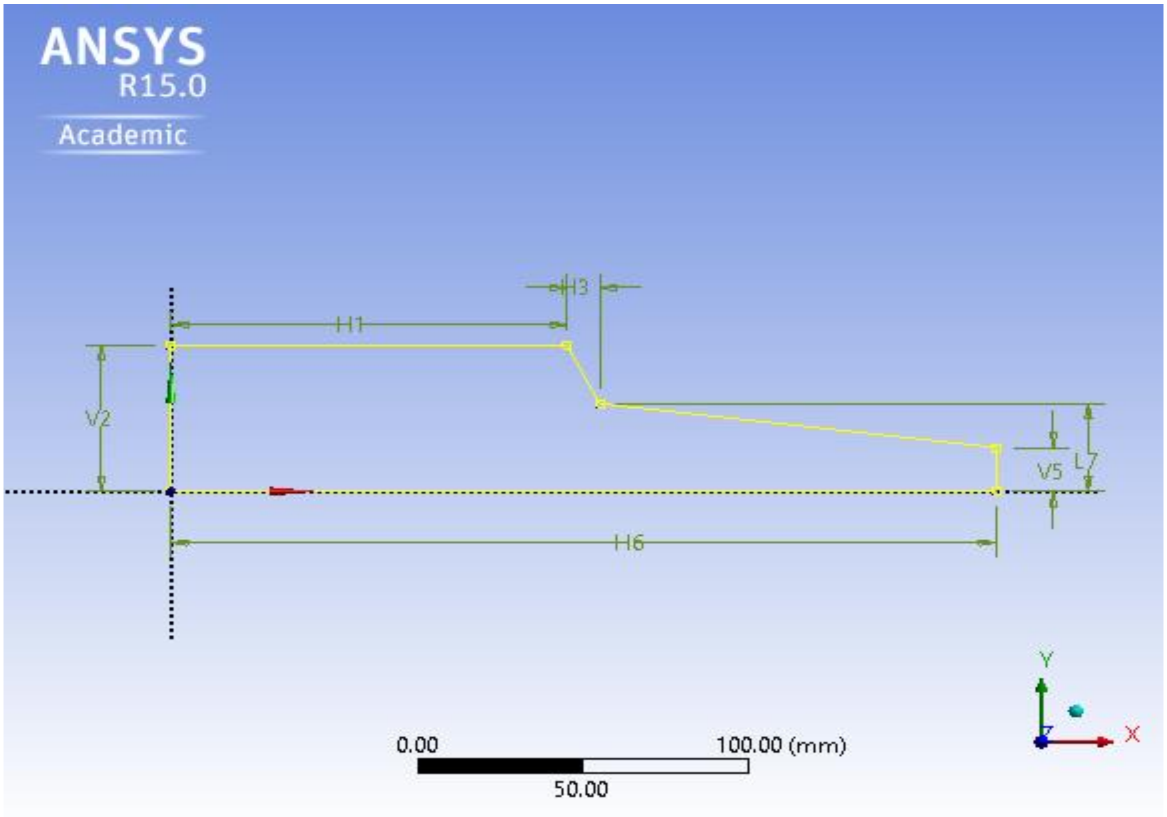


Fig 7. Design of the work piece for CFD modelling

The design of the work piece and media cylinder was done in Design Modeler of ANSYS15.0

The Measurements are as follow w.r.t the above given figure:

H1 = 120mm.

H3 = 10mm.

H6 = 250mm.

L7 = 30mm.

V2 = 50mm.

V5 = 15mm.

3.2.4 Mesh Report and diagram of work piece with fixture by ANSYS

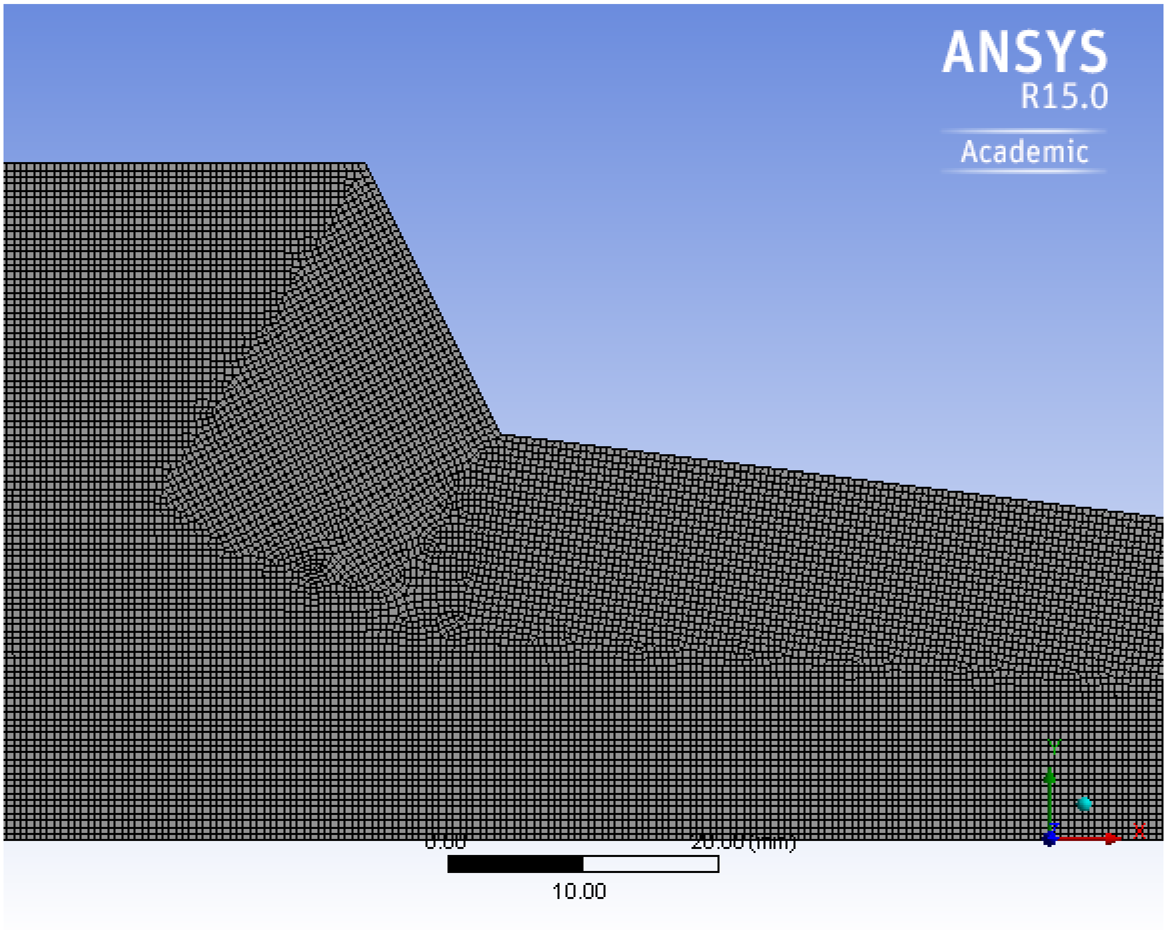


Fig 8. Meshing of the work piece and fixture

Units

TABLE 1

Unit System	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A3)

Geometry

TABLE 2
Model (A3) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\anSUman\Desktop\Project\ansys final\taperedpipe_files\dp0\FFF\DM\FFF.agdb
Type	DesignModeler
Length Unit	Meters
2D Behavior	Plane Stress
Bounding Box	
Length X	250. mm
Length Y	50. mm
Properties	
Volume	9100. mm³
Surface Area(approx.)	9100. mm²
Scale Factor Value	1.
Statistics	
Bodies	1
Active Bodies	1
Nodes	37090
Elements	36512
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\anSUman\AppData\Local\Temp
Analysis Type	2-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	No

TABLE 3
Model (A3) > Geometry > Parts

Object Name	*Surface Body*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Coordinate System	Default Coordinate System
Thickness	1. mm
Thickness Mode	Refresh on Update
Reference Frame	Lagrangian
Material	
Fluid/Solid	Defined By Geometry (Solid)
Bounding Box	
Length X	250. mm
Length Y	50. mm
Properties	
Volume	9100. mm³
Centroid X	99.432 mm
Centroid Y	20.842 mm
Centroid Z	0. mm
Surface Area(approx.)	9100. mm²
Statistics	
Nodes	37090
Elements	36512
Mesh Metric	None

Coordinate Systems

TABLE 4
Model (A3) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. mm
Origin Y	0. mm
Directional Vectors	
X Axis Data	[1. 0.]
Y Axis Data	[0. 1.]

Mesh

TABLE 5
Model (A3) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	100
Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	1.0 mm
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Slow
Span Angle Center	Fine
Minimum Edge Length	15.0 mm
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	2
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Assembly Meshing	
Method	None
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	Yes
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	CFD
Element Midside Nodes	Dropped
Number of Retries	Default (0)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Use Sheet Thickness for Pinch	No
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Sheet Loop Removal	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	37090
Elements	36512
Mesh Metric	None

TABLE 6

Model (A3) > Mesh > Mesh Controls

Object Name	*Face Sizing*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Type	Element Size
Element Size	0.5 mm
Behavior	Soft

Named Selections

TABLE 7

Model (A3) > Named Selections > Named Selections

Object Name	*inlet*	*outlet*	*top cylinder*	*topworkpiece*	*toptrans*	*bottom*
State	Fully Defined					
Scope						
Scoping Method	Geometry Selection					
Geometry	1 Edge					
Definition						
Send to Solver	Yes					
Visible	Yes					
Program Controlled Inflation	Exclude					
Statistics						
Type	Manual					
Total Selection	1 Edge					
Suppressed	0					
Used by Mesh Worksheet	No					

3.3 Parameter setting:

Material: Titanium Grade 2, Annealed

Composition: H-0.015%, C- 0.1%, Ti - 99.2%, O - 0.25%, Fe - 0.3%, N-0.03%,

Density: 4510kg/m^3

Brinnel hardness no: 98

Ultimate tensile strength: 730 MPa

Yield strength: 340 MPa

Shear strength: 380 MPa

Media: Patented Media [35, 36] , viscosity = 510kg/Pa-sec

Abrasive: Aluminum Oxide

Diameter = Da = 40 µm.

3.4 Boundary conditions

- A fully developed flow condition is there.
- Inlet has constant velocity input and outlet has constant pressure output.
- No slippage along the wall.
- Along the axis, it is made axis symmetric.
- The inlet pressure is given 40 bar.
- Volume fraction of abrasive is 40%.

The following assumptions are made to carry out the calculations easily:

- Homogenous medium.
- Quasistatic flow should be there. Also laminar and incompressible.
- Axis symmetric flow.
- No turbulence or swirling in the flow.

3.5 Steps of Fluent analysis

- Scale was checked to mm.
- Domain extent, face area, volume statistics and mesh was checked.
- Solver type set to pressure based; the setting of velocity formulation was set to absolute; the time function was made steady; analysis made 2D type; space made axisymmetric.
- The model was made Eulerian type with implicit volume fraction.
- Media with density (1400kg/m^3) and viscosity (510kg/Pa-s)-was created along with aluminum oxide for abrasive. N in solid titanium was created.
- In Phases-media was made primary phase with schiller naumann drag coefficient

  Secondary phase was constituted by aluminum oxide with granular properties and diameter 40µm.
- In Boundary conditions zone, inlet was given a constant velocity inlet with a gauge pressure of 40 bar for the medium. And the phases were given individual velocities of 0.15 m/s. with volume fraction in phase 2 as 40 %.
- Outlet was made pressure type with 1 bar pressure.
- All others were kept at constant.
- In Monitors-residuals were brought down to 0.000006 and convergence criteria was set to absolute.
- Solution initialization method was made standard and computed from all zone and then initialized.
- Then calculation was done.

The solution converged at 1467 iterations.

3.6 CFD Results: Physical Report

Table 8. Domain Physics for FFF

Domain - surface body	
Type	cell

Table 9. Boundary Physics for FFF

Domain	Boundaries	
surface_body	**Boundary - bottom**	
	Type	AXIS
	Boundary - inlet	
	Type	VELOCITY-INLET
	Boundary - outlet	
	Type	PRESSURE-OUTLET
	Boundary - periodic 1	
	Type	PERIODIC
	Boundary - periodic 1 shadow	
	Type	PERIODIC
	Boundary - top_cylinder	
	Type	WALL
	Boundary - toptrans	
	Type	WALL
	Boundary - topworkpiece	
	Type	WALL

3.6.1 Pictures

Figure 9. velocity distribution

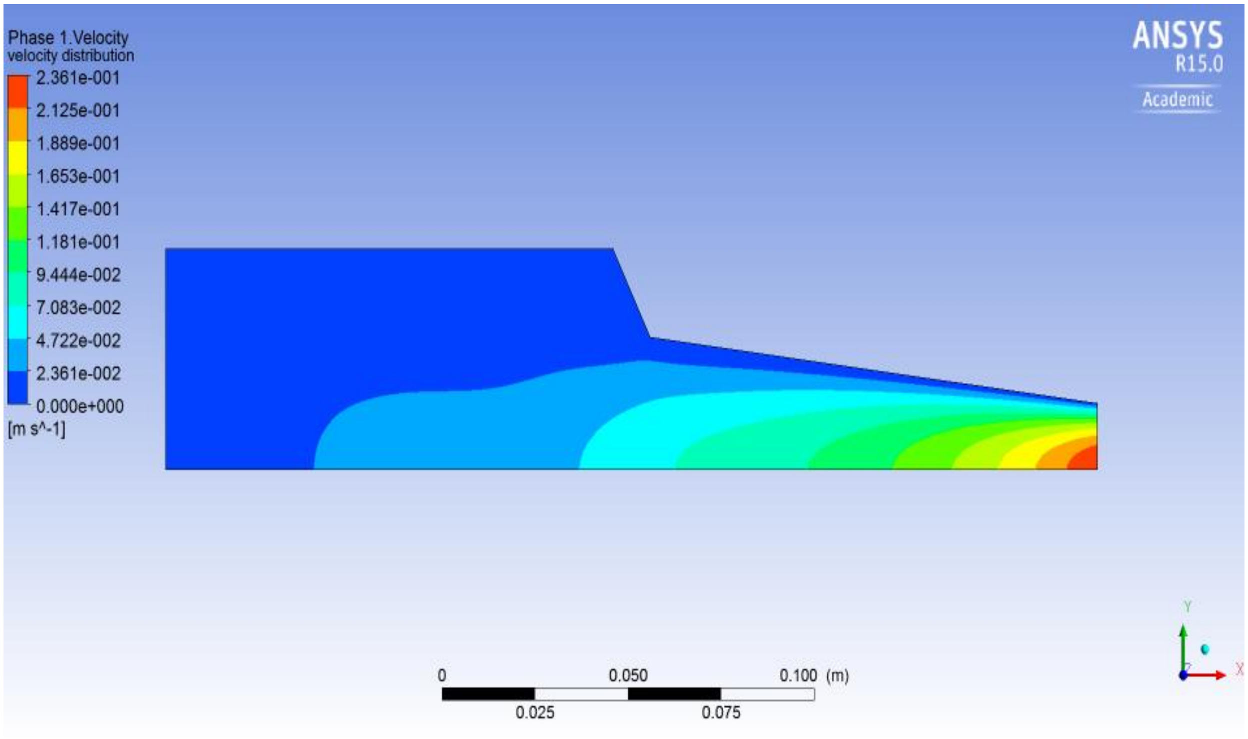


Figure 10. velocity vector

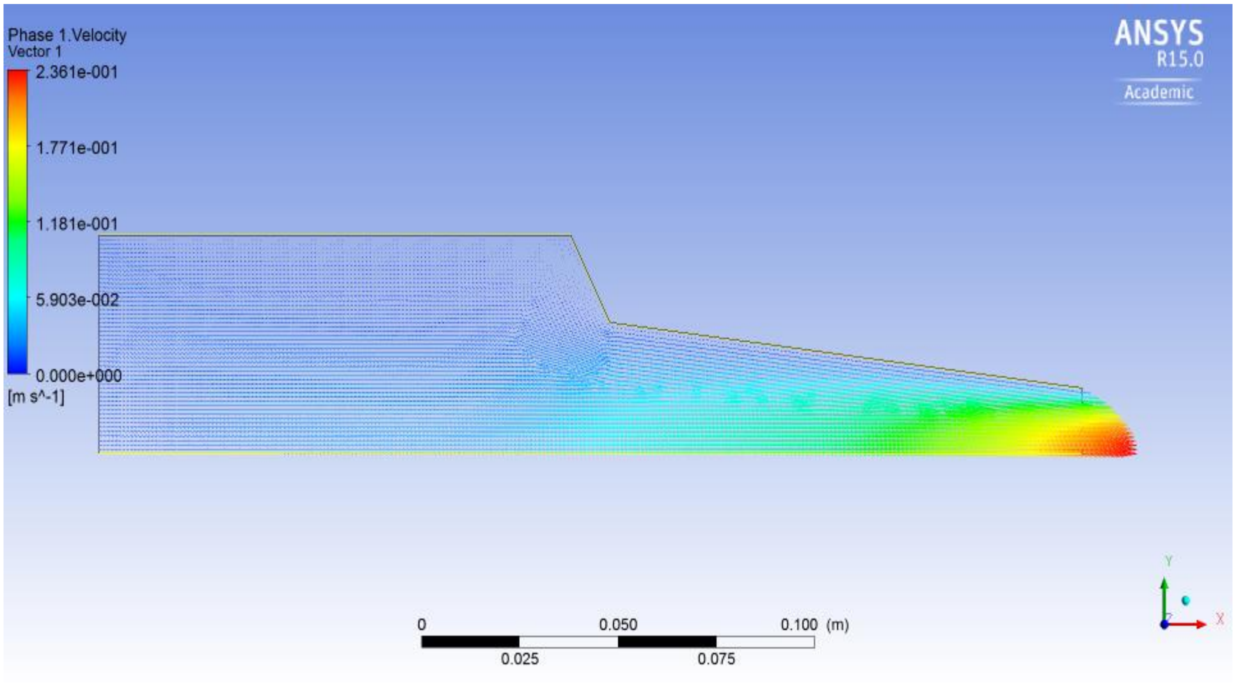


Figure 11. pressure distribution

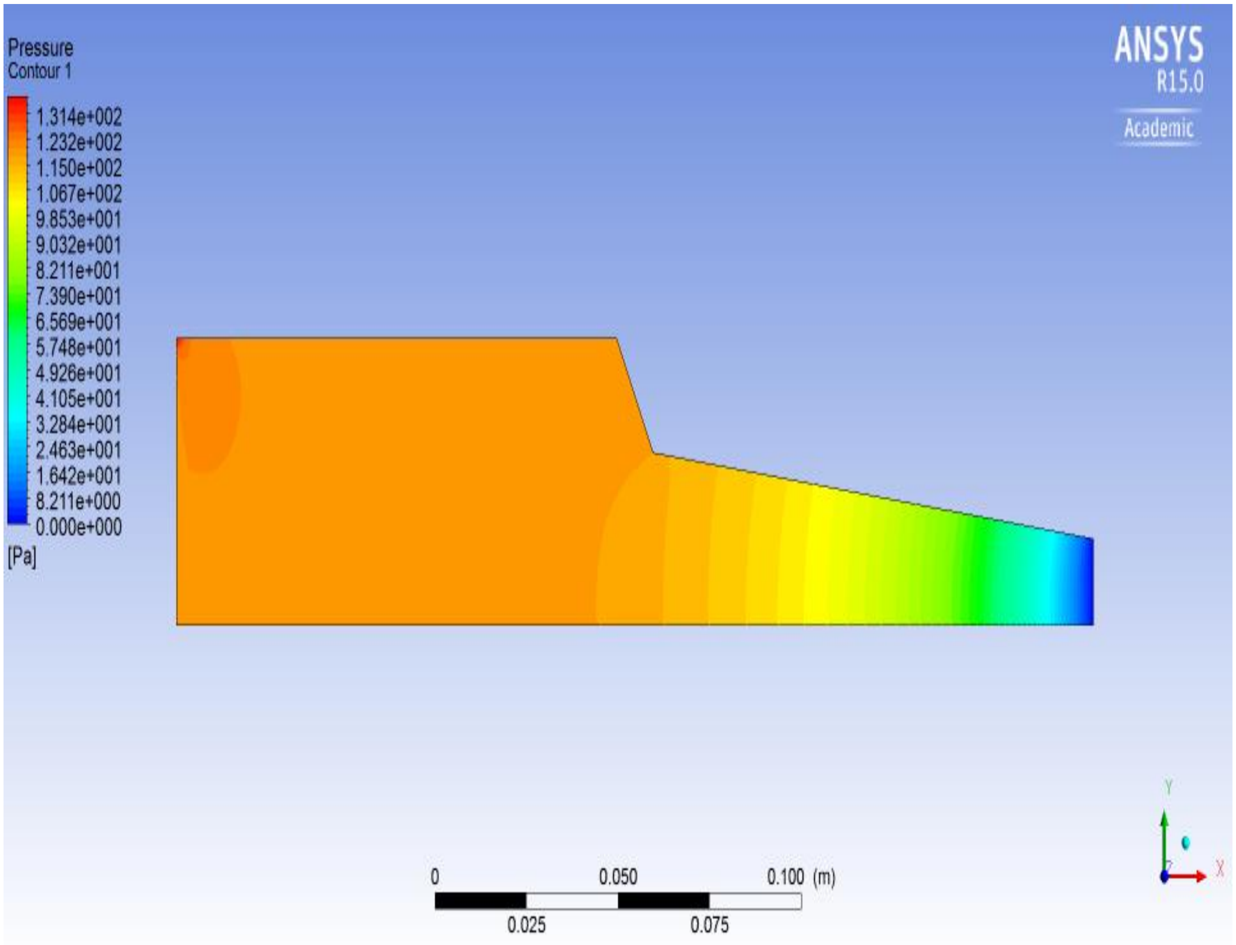


Fig 12. Chart 1.phase velocity vs position

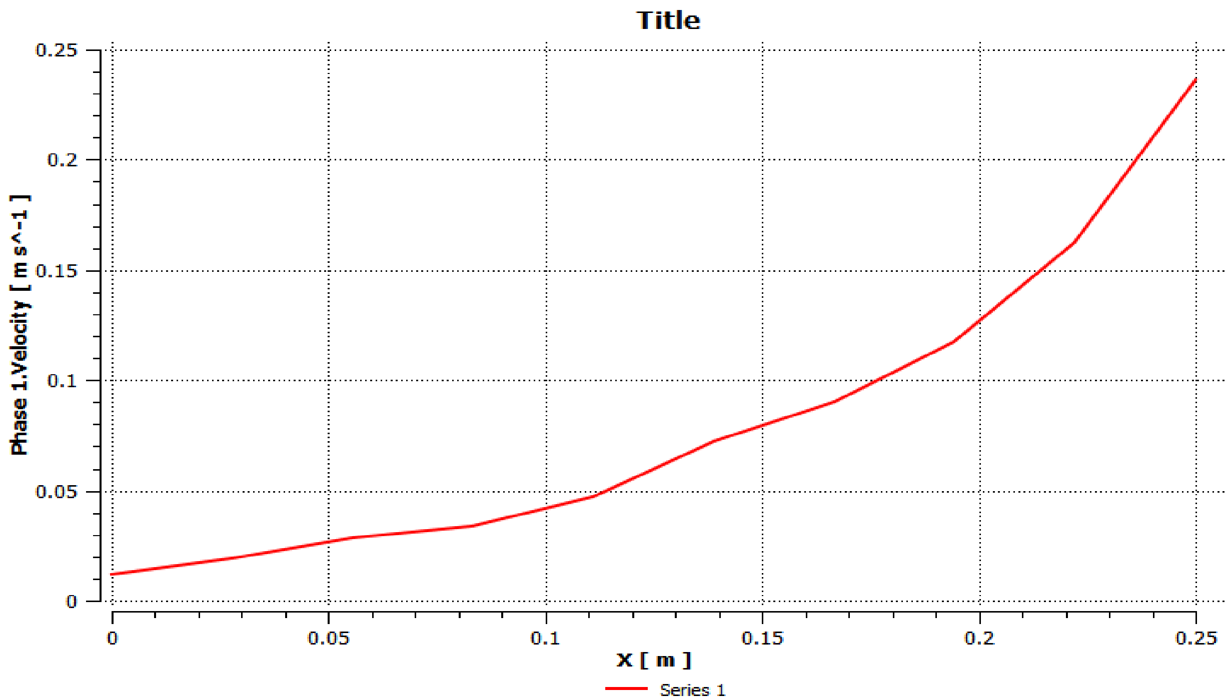


Fig. 13. Chart 2.pressure vs position

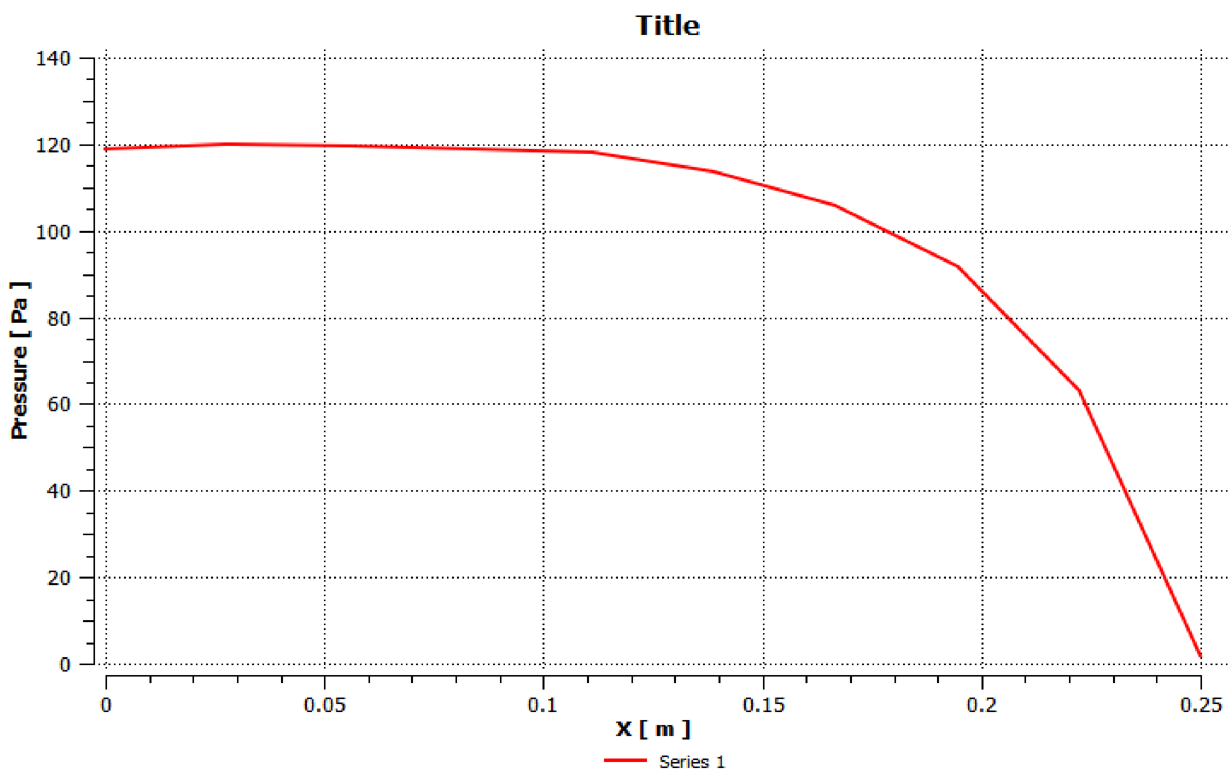


Fig 14. Chart 3.axial wall shear vs positon

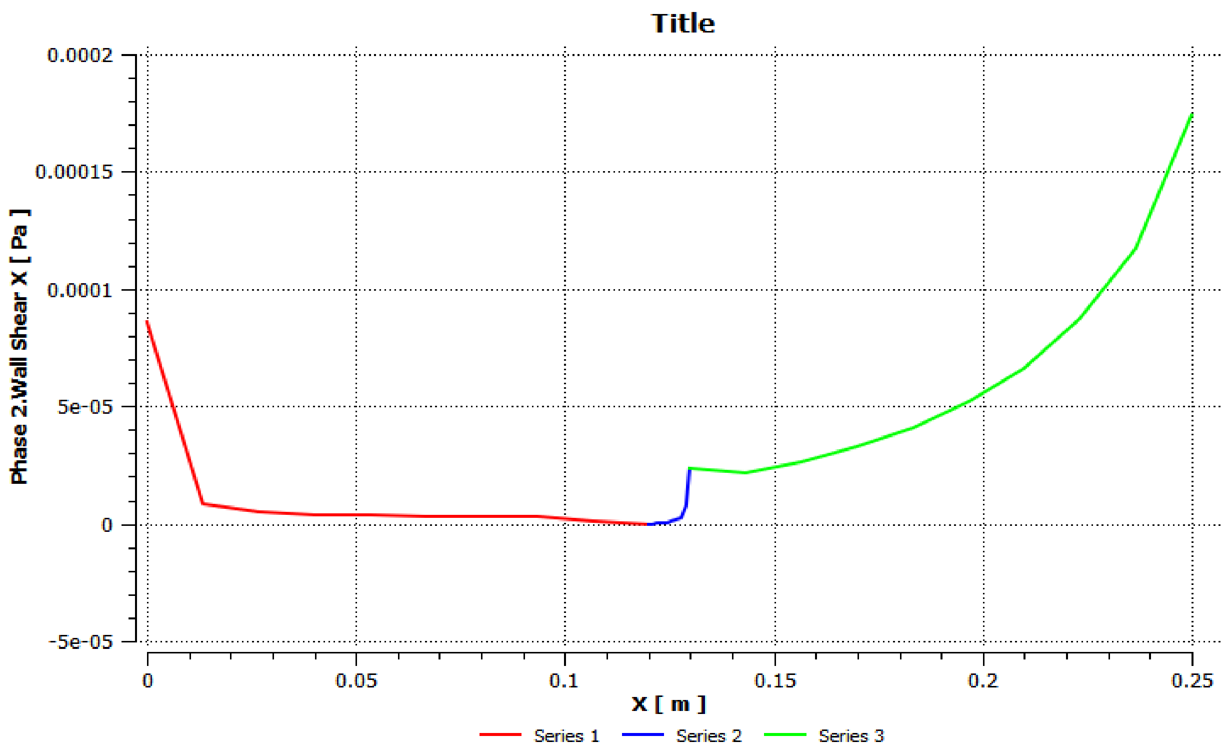


Fig. 15 Chart 4.radial shear vs position

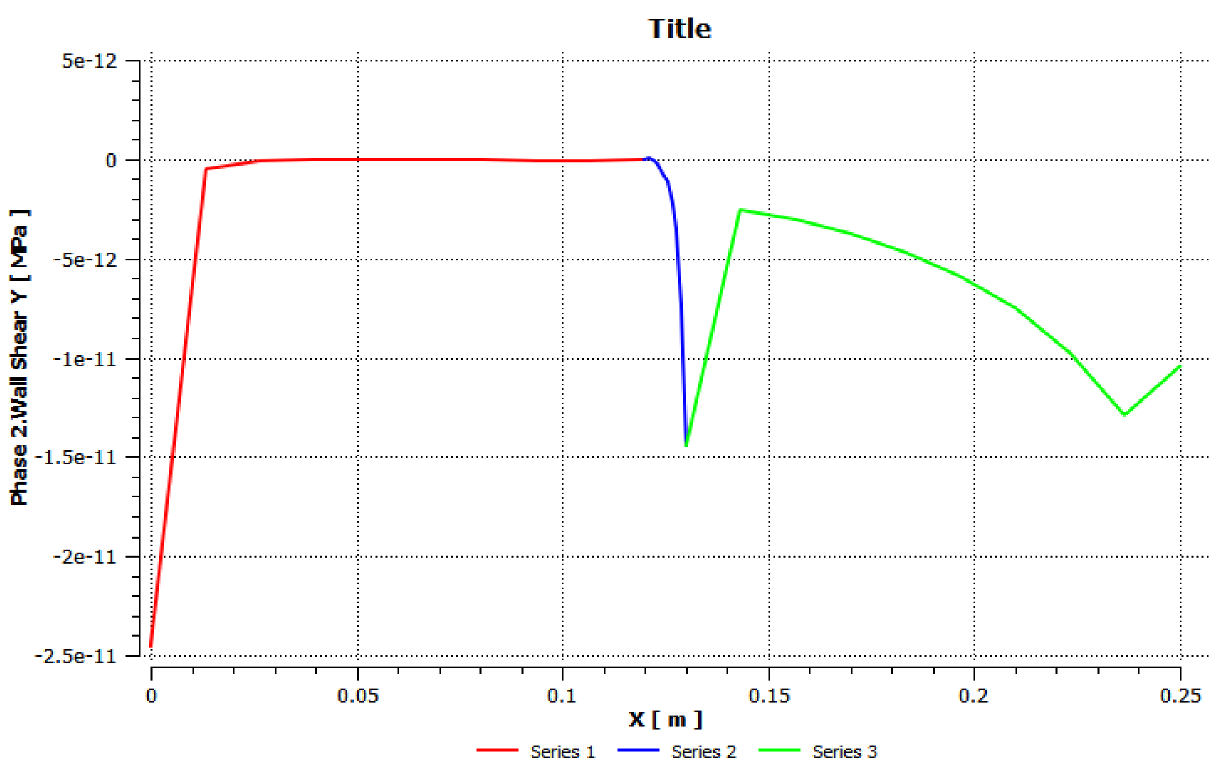


Fig. 16. Chart 5 axial shear vs position

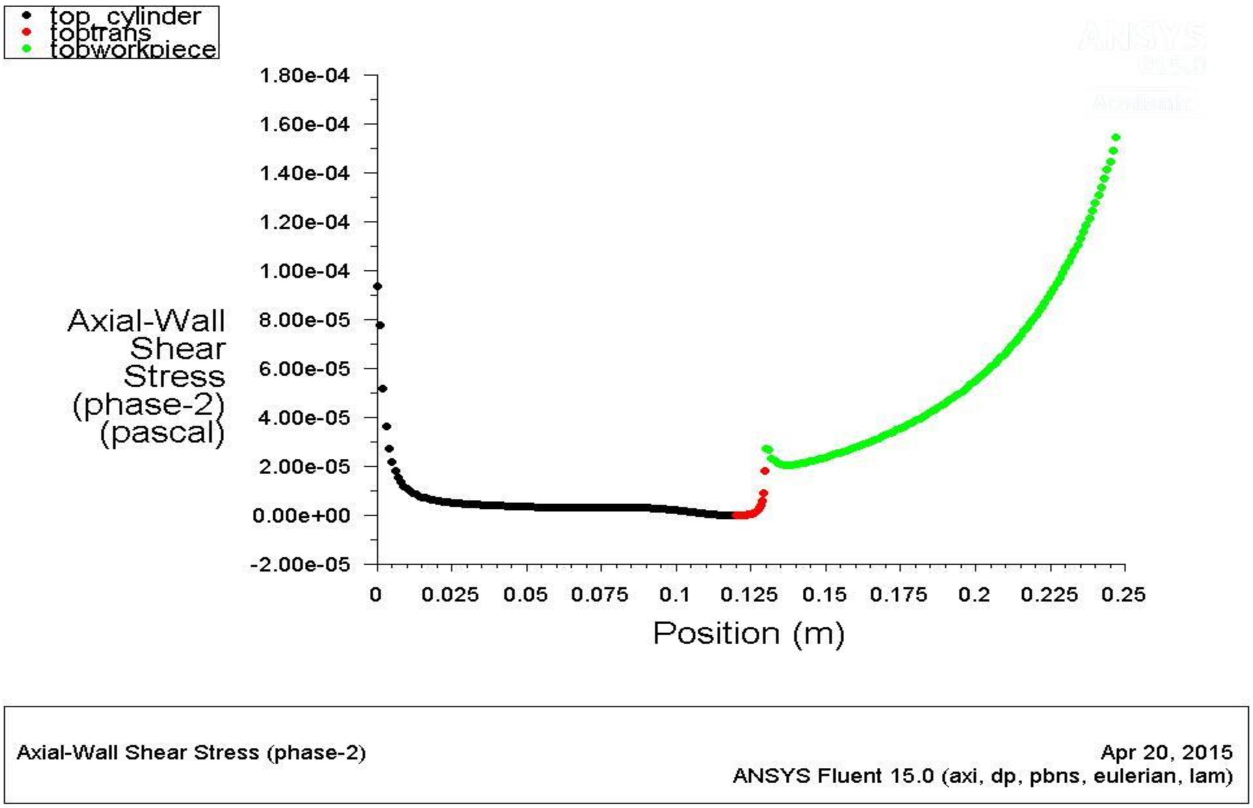


Fig. 17 chart 6 Radial wall shear vs position

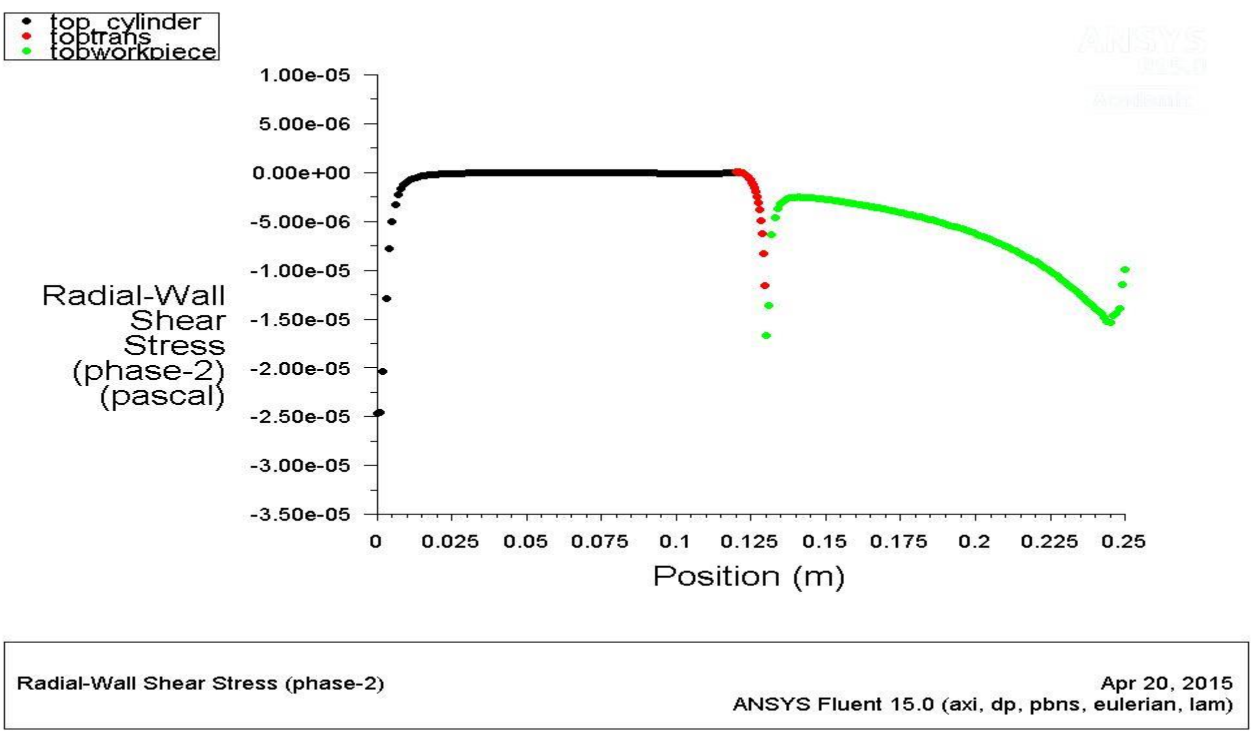


Fig. 18 chart 7 velocity magnitude vs position

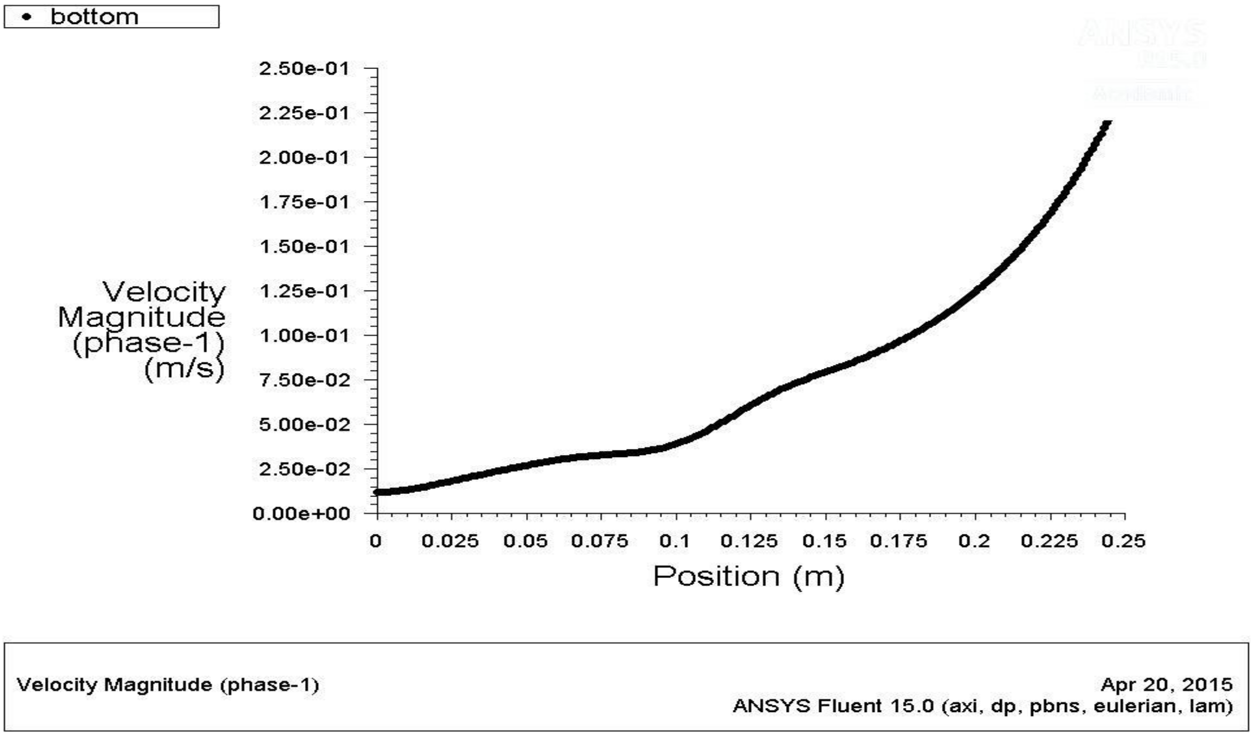


Fig. 19 chart 8 static pressure vs position

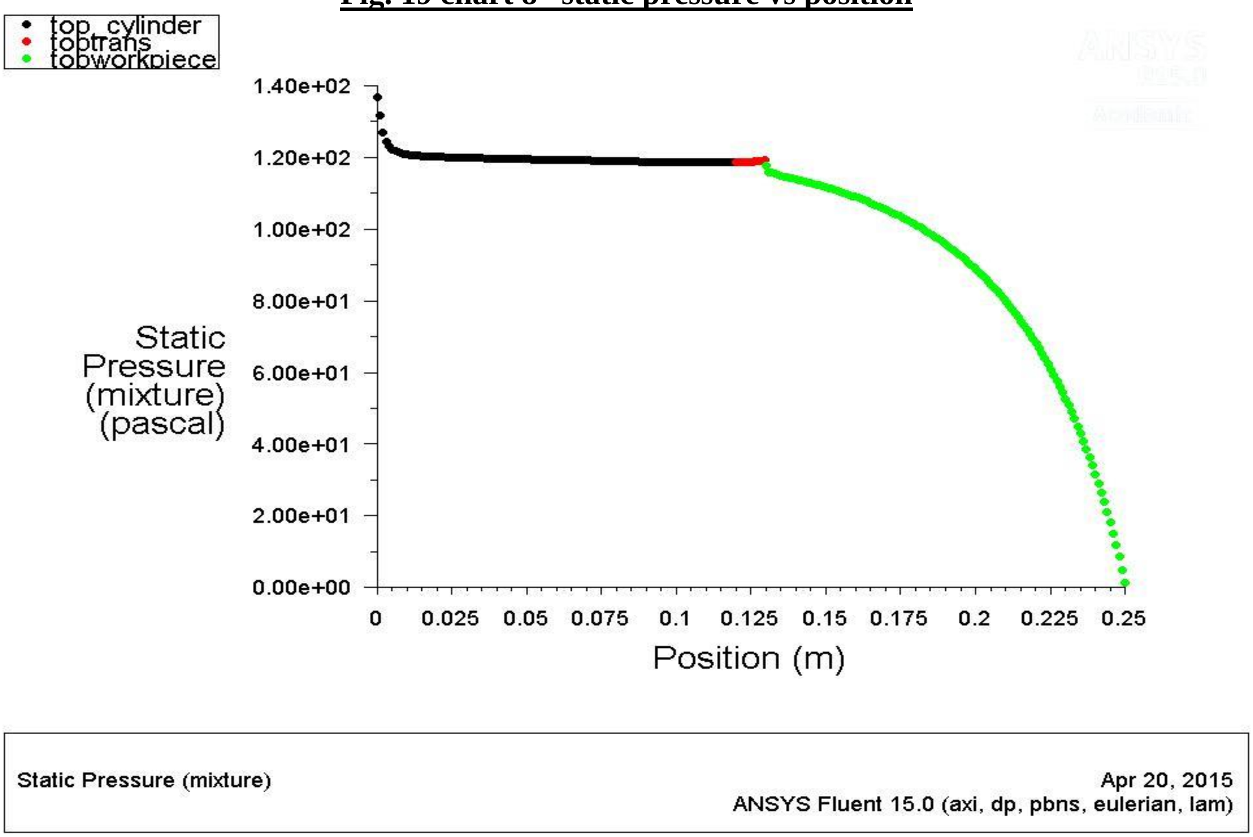


Fig. 20 chart 9 radial shear vs w/p length

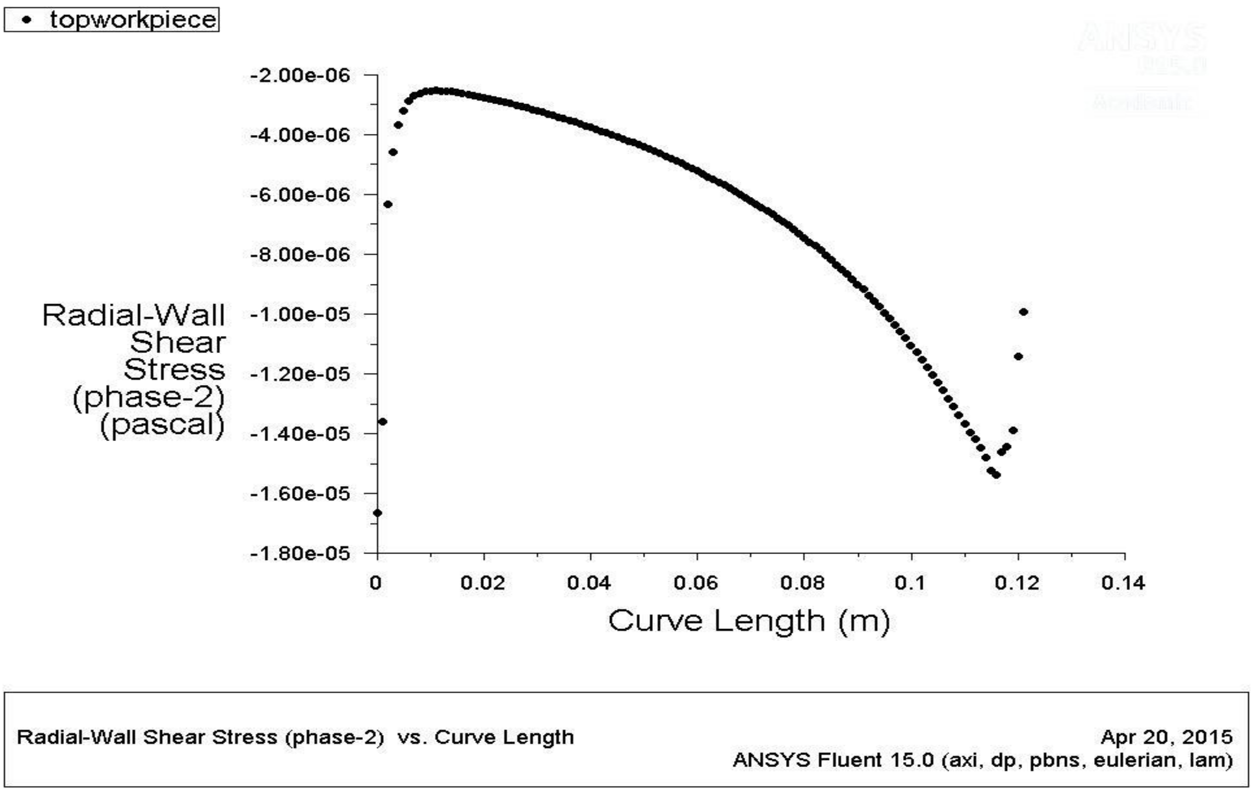
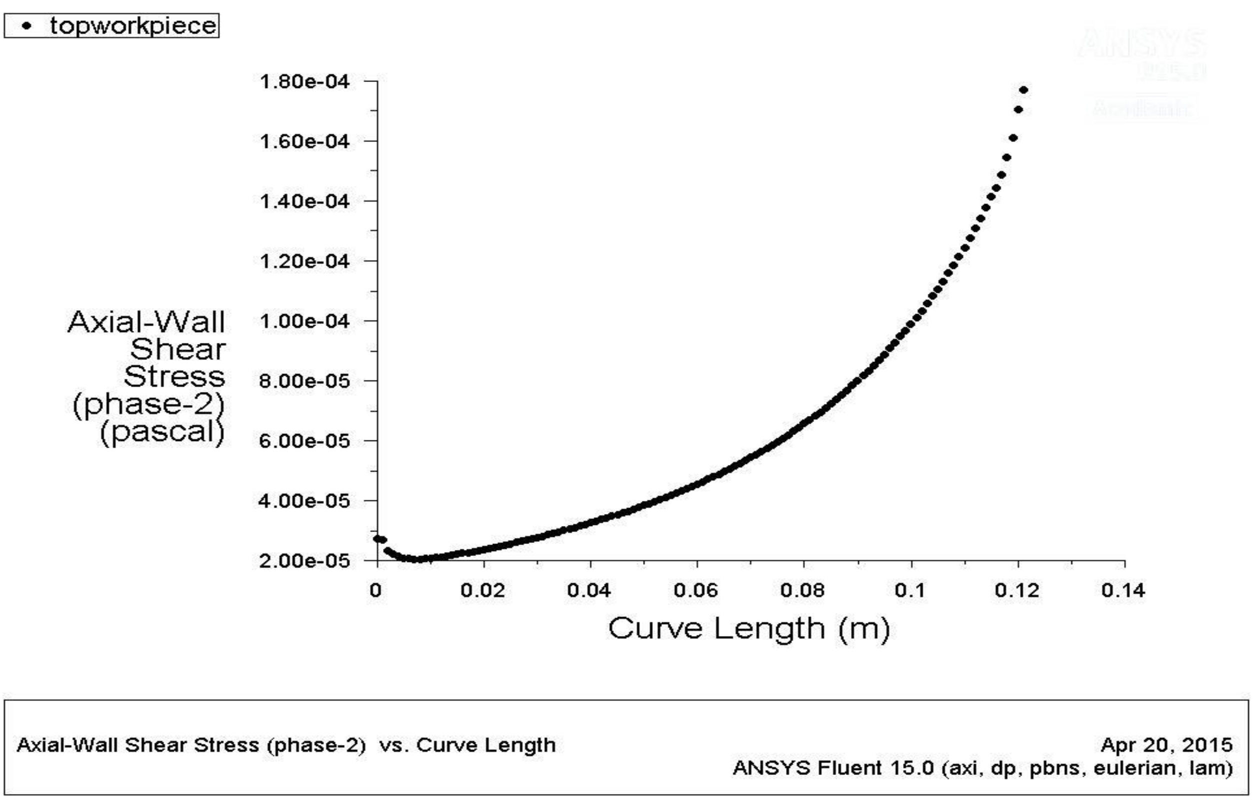


Fig. 21 chart 10 axial wall shear vs w/p length



Segment 4

4.1 Formulation of MRR taking cylindrical work piece

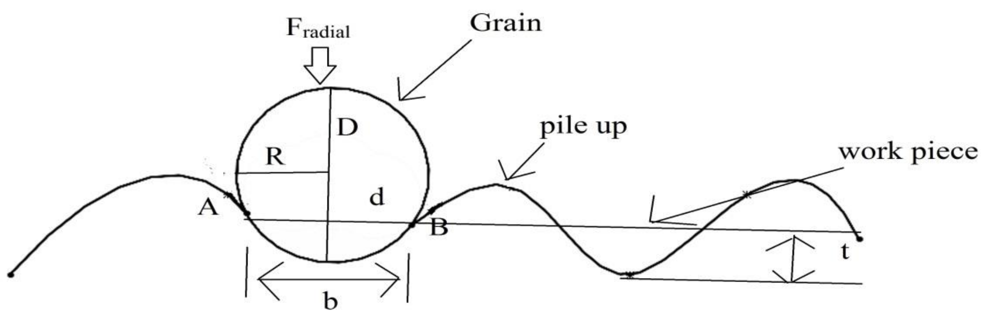


Fig 22.Abrasive grain work piece interaction

In the figure above, R= Grain Radius

t = depth of indentation

The normal force on a indenting grain can be calculated as

$$F_n = \sigma_{rad} * A \qquad \dots (1)$$

Where σ_{rad} = radial stress. ; Fn = normal force; A = projected area of sphere.

Let 'r' be the radius of the indentation.

So by Pythagorean law

$$R^2 = r^2 + (R-t)^2$$

=> $t = D/2 – (D^2/4 – r^2)^{1/2}$ ....(2)

Let H_w be the hardness of the work piece.

Then the force exerted on it is $F_n = H_w * \pi r^2$ …(3)

Putting value of r^2 from eq. 3 in eq. 2

$$t = D/2 - (D^2/4 - F_n/\pi H_w) \quad \ldots(4)$$

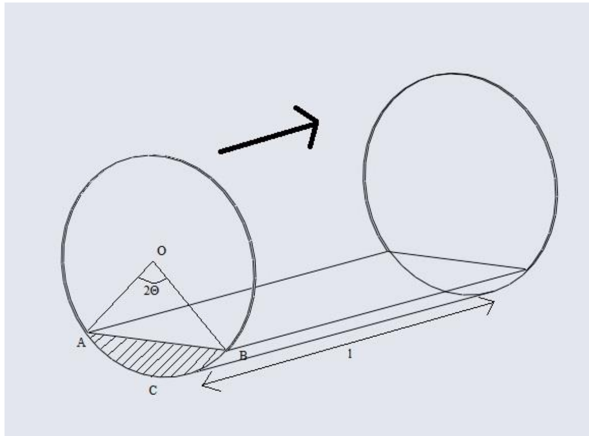


Fig. 23 Abrasive particle showing ploughing.

Each spherical particle generates a groove while interacting with the work piece.

So volume removed by one grain is =

Area of the hatched cross section in the figure * length of the abrasive grain moved (L_m).

From figure.

AB = previously found diameter of indentation.

Ar of arc ABCA = Ar OACB – Ar OAB.

Ar of sector OACB=

$= \pi r^2 * (\theta/360)$.

$$\text{Sin } \theta = \frac{r}{R}$$

$$= \frac{2\sqrt[2]{(Da-d)t}}{D}.$$

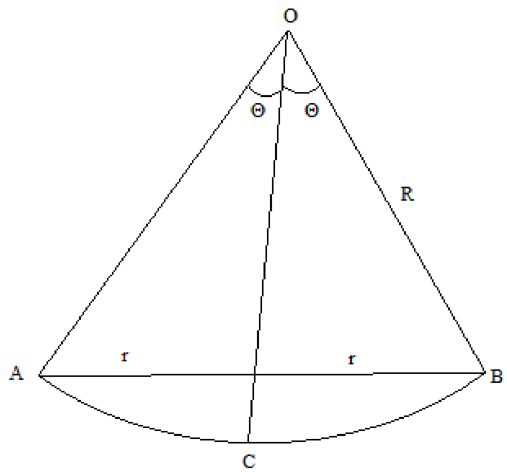


Fig 24. The cross section of abrasive.

Area of triangle OAB= 0.5*AB*OD

$$= \sqrt{t(Da-t)}\left(\frac{Da}{2}-t\right). \quad \ldots (5)$$

$$\text{Area of OACB} = \frac{D^2}{4}\sin^{-1}\left\{\frac{2\sqrt{t(Da-t)}}{Da}\right\}. \quad \ldots (6)$$

Material Removal by abrasive grain

$$V = \left\{\frac{D^2}{4}\sin^{-1}\left\{\frac{2\sqrt{t(Da-t)}}{Da}\right\} - \sqrt{t(Da-t)}\left(\frac{Da}{2}-t\right)\right\}L_w. \quad \ldots (7)$$

Where the subscript 'w' stands for work piece.

Let the volume fraction of abrasive be x. then x% of the media is covered with abrasives.

Now let us consider a unit thickness of the media on the inside surface of the work piece cylinder. Its volume will be $2\pi R_w L_w$.

The volume of abrasives in this volume = $2\pi R_w L_w x = V_a$.

So total no of active grains $N_T = V_a$ / volume of each abrasive = $\frac{3RwLw}{2Ra^3}$. … (8)

Assuming the distance moved by each grain is equal to the length of the work piece, so the material removal =

$$= N_T \left\{\frac{Da^2}{4}\sin^{-1}\left\{\frac{2\sqrt{(Da-t)t}}{D}\right\} - \sqrt{t(Da-t)}\left(\frac{Da}{2}-t\right)\right\} L_w.$$

$$= \frac{3RwLw^2}{2Ra^3}\left\{\frac{Da^2}{4}\sin^{-1}\left\{\frac{2\sqrt{t(Da-t)t}}{D}\right\} - \sqrt{t(Da-t)}\left(\frac{Da}{2}-t\right)\right\}. \quad \dots (9)$$

4.2. Formulation of MRR taking tapered work piece and subsequent calculation

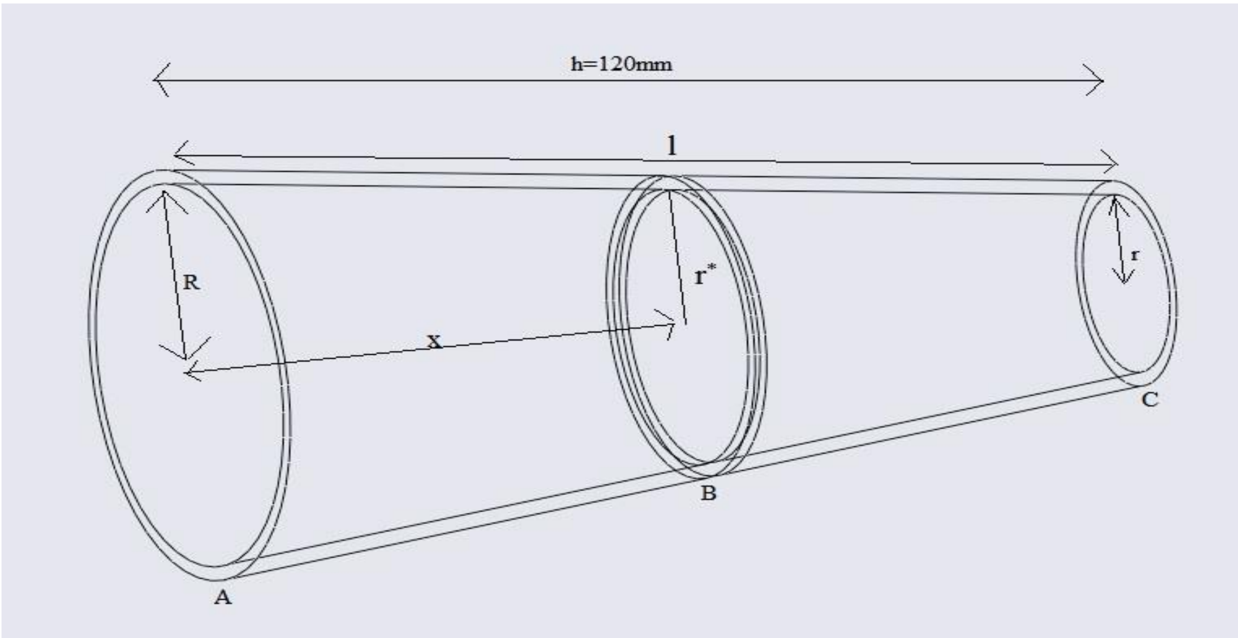


Fig. 25. Showing the differential part of the work piece.

In the present study we have taken this work piece and try to obtain a method to get MRR theoretically.

We know from eq. 4 the depth of indentation is $t = Da/2 – (Da^2/4 – F_n/\pi H_w)$

In this case 'F_n' varies with distance x from the point A (refer figure) to the exit. That would mean the force varies from point to point and so will the depth of indentation. But we need a uniform surface finish. But as the work piece is not of very significant length so the force can be calculated as differential function of x and then integrated over the whole surface to give the average force and then the calculations can proceed smoothly. If we were to calculate the exact force at a particular point this would require a double integration function and the calculations will become very complex on paper. So for making it smooth we will derive a formula here and compare it with the results obtained from the CFD analysis of the same.

A piston applies a constant pressure P on the media which is forced through the work piece. The media is considered homogenous taking into account the very small abrasive size. So the pressure is distributed in all directions uniformly. So F/A remains constant.

The media is given an initial velocity 'v' at a constant pressure p.

By law of continuity $A_1V_1 = A^*V^*$ where * is represents the varying area and velocity through the work piece.

Taking a thin section in the work piece as shown in above figure at a distance 'x' from point A, we can apply Bernoulli's equation.

$$P_1 + \rho gh + \frac{1}{2}\rho v_1^2 = P_2 + \rho gh + \frac{1}{2}\rho v_2^2.$$

P_1 is the pressure at the start of the work piece,

We have initial conditions as velocity in media cylinder = 0.015m/s.

Let 'Ar' denote the area of the cylindrical cross section.

Now between points A and B the following relation holds true.

$$\frac{h}{R-r} = \frac{h-x}{r*-r}$$ (From geometry of the figure).

- $r^* = r + (1- x/h)(R-r).$ ....(10)

  Where R and r are the larger and smaller radii of the work piece ends respectively.

  Cross section at point B = Ar^*.

  Now $A_1V_1 = A^*V^*$.

- $$V^* = \frac{R^2}{r+(1-\frac{x}{h})(R-r)} .$$ ...(11)

Taking the differential strip with thickness dx as shown in figure.

$A_m = \pi 0.05^2/4\ m^2$.

$A_1 = \pi 0.03^2/4\ m^2$.

$V_1 = 1/30$ m/sec.

$P_m =$ pressure in media cylinder = 40 bar.

Density of the multiphase mixture= 2420kg/m^3.

$$P_m + \frac{1}{2}\rho v_m^2 = P_1 + \frac{1}{2}\rho v_1^2.$$

Solving this, we get $P_1 = 39.99$ bar.

Now at the differential section $P^* = 4052998.83 - \frac{x}{.24-x}$. …(12)

$dF_n = P^* dA$ (where $dA = 2\pi r^* dx$)

putting the value of P^* from eq. 12 and integrating for F_n we get the force due to radial stress as the hydraulic pressure is perpendicular and the stress can be assumed to be radial stress.

So we get the average value of F_n to be = $43088.0363 \times 10^{-14}$.

4.2.1 Radius of indentation

For D_a=40µm; $H_w = 98$; $F_n = 4.308 \times 10^{-10}$ From eq. 4 we get.

$F_n = \pi H_w r^2$.

Radius of indentation $R_i = 1.92 \times 10^{-6}$ m.

4.2.2 Depth of indentation

With the above values we can get the depth of indentation from eq. 4.

t = $\mathbf{3.559 \times 10^{-8}}$**.**

4.2.3 Calculation of MRR

The MRR of a single grain taking into account that the length of the work piece is the length of the grain traversal is same as that in eq. 9.

But when it comes to overall MRR a bit of changes are there.

Let the volume fraction of abrasive be x. then x% of the media is covered with abrasives.

And volume of unit thickness of media on work piece walls is = $\sqrt{h^2 + (R-r)^2}\,\pi(R+r)$.

The volume of abrasives in this volume = $\sqrt{h^2 + (R-r)^2}\, x\pi(R+r)$.

So total no of active grains $N_T = V_a$ / volume of each abrasive =

$$\frac{3x\pi(R+r)\sqrt{h^2+(R-r)^2}}{4\,Ra^3} \text{……….}(13)$$

Total predicted MRR of the system=

$$\left\{\frac{6x\pi(R+r)\sqrt{h^2+(R-r)^2}}{Da^3}\right\} X \left\{\left\{\frac{Da^2}{4}\sin^{-1}\left\{\frac{2\sqrt{t(Da-t)}}{Da}\right\} - \sqrt{t(Da-t)}\left(\frac{Da}{2} - t\right)\right\}\right\} \text{… (14)}$$

R= 0.03 m

r= 0.015m

Da= 40μm

h= 0.12m

t= 3.559×10^{-8}

So MRR is calculated as = $55.23 \times 10^{-14.}$

4.3 Results and Discussion

4.3.1 Results

- The CFD model that had been applied to the present case was tested and the results were verified with a previously done work on a cylindrical work piece.
- The crucial factor of the problem was the calculation of proper indentation force, or radial stress (from CFD analysis). The CFD analysis gave a value of 0.15 Pa for Radial stress. Whereas the theoretical normal force gave a result of 0.26 Pa. This fluctuation might be due to the fact that a no. of assumptions were taken while its calculation.
- However the errors were within the tolerance limits.

4.3.2 Limitations of the proposed model

- The medium is assumed to be perfectly homogenous.
- The calculation of no of active particles involved assuming a unit thickness of media on the inner wall which is not always feasible.
- The particle is assumed to be abrading the whole length of the work piece.
- It is also not very helpful as this model suggests that the abrasives which are not in contact with the work piece never come in contact.

Segment 5

Conclusion .

- The axial and radial stresses at the work piece were found through CFD analysis of the tapered pipe.
- Material removal rate was formulated and also calculated from this simulation.
- An existing model of material removal was selected and modified according to suitable assumptions.
- The results came with a little error due to the assumptions taken during their calculations.
- However the errors were within the limitations of experimental procedure.
- Future study into the model and modifications can be done to the current model.

Segment 6

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