CFD Analysis of Nozzle in Abrasive Water Suspension Jet Machining

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Abstract- *The cutting nozzle of AWJM is one of the important elements of jet machining since it converts pressure energy into kinetic energy. This kinetic energy of jet gives necessary impact to remove the material from the work piece. The nozzle subjected to variations in flow of slurry, velocity of abrasive particles, density of abrasive particles, etc. therefore it is necessary to design the cutting nozzle under these circumstances. This paper presents the Compressed Fluid Dynamics (CFD) analysis of the cutting nozzle for measuring the parameters to improve the nozzle performance. This analysis can be highly helpful for understanding nozzle wear during the AWSJ machining process.*

Keywords- Abrasive water suspension jet (AWSJ) machining, fluid flow, jet exit kinetic energy, nozzle geometry, nozzle wear.

I. INTRODUCTION

In AWJM, the water jet stream accelerates abrasive particles, not the water, to cause the material removal. After the pure water jet is created, abrasives are added using either the injection or suspension methods. The important parameters of the abrasives are the material structure and hardness, the mechanical behavior, grain shape, grain size, and distribution. The basic machining system of AWJM incorporates the following elements.

- Water Supply Arrangement
- Abrasive Material Handling System
- Control Valves and Mixing Chambers
- Cutting Nozzles

The AWJM includes 70% of water mixes with 30% abrasive particles in the mixing chamber by controlling valves. The pressurized slurry passed through the cutting nozzle to impact on the work piece. As a result of the process, the high velocity slurry tries to remove the particles of the work piece and material will remove from the work piece.

Advanced water jet and AWJ machines are now available where the computer loads a computer-aided design (CAD) drawing from another system. The computer determines the starting and end points and the sequence of operations. The operator then enters the material type and tool offset data. The computer determines the feed rate and performs cutting. Other machining systems operate with a modem and CAD/computer-aided manufacturing (CAM) capabilities that permits transfer from CATIA, AUTOCAD, IGES, and DXF formats. The computer runs a program that determines, in seconds, how to minimize the waste when cutting from blocks or plates. The model has been created in CATIA with various models. Model 1 shows the existed nozzle design. The design has been adopted by changing nozzle taper angle in model 2. In model 3, the ceramic coting of 1 mm thickness is provided to inspect the CFD analysis in ANSYS (CFX).

II. LITERATURE STUDY

Water jet technology was slowly developing, but it wasn't until the 1970s that the first commercial water jet cutting machines were built in the USA. These machines were capable of creating a 40,000 bar pressure, and water jet mining – combining a drill with the water jet – was a growth area. In 1972 Professor Norman Franz of Michigan, working with McCartney Manufacturing Company, was first to install an industrial water jet cutter.

Md. G. Mostofa et. al [1] concluded that the Water jet cutting is an appealing technology for cutting thick materials with zones that must not be affected by heat. Results show that nozzle length has an effect on the mixing of water, air, and the abrasives, and that the velocity of the water jet influences the erosion rate at the nozzle wall. This investigation reveals that the erosion in the nozzle body is higher at the initial zone and that as the length of the nozzle length increases, the volume fraction of air increases accordingly. M. Rajyalakshmi [2] studied various statistical and modern approaches are applied to optimize these process parameters to improve the performance characteristics. But most of the authors considered common process parameters like hydraulic pressure, traverse speed, stand-off distance and abrasive flow rate. Other parameters can also be considered for optimization, which influence the quality parameters. In the presented work an attempt is made to review the research work carried out so far in the area of AWJM. In the work of Saurabh verama et.al [3], the effect of geometrical parameters of single step nozzle and abrasive size on skin friction coefficient at the wall of nozzle due to wall shear stress and jet exit kinetic energy has been analyzed by ANSYS software. This analysis is totally depends on nozzle geometry and nozzle material is taken same for all cases. This analysis can be highly helpful for understanding nozzle wear during the AWSJ machining process. Deepak D et. al [4] concluded that Increase in inlet operating pressure results in significant increase in the wall shear stress. The wall shear stress approach peak values corresponding to the sudden change in the flow passage geometry at the critical section. Increase in the inlet operating pressure results in linear increase in the average exit kinetic energy of jet. Rakesh Kumar Sahu et. al [5] obtained the optimized value of SFC through TLBO is 0.001197 and it is closer to Analyzed value of SFC. In the present work, According to the structure of nozzle computational domain has been modeled using commercially available preprocessor routine called GAMBIT, and CFD Analysis has been performed in ANSYS (fluent) to obtain the values of SFC for different values of parameters. Based on the Analysis at the critical section of nozzle an empirical formula has been developed for nozzle geometry. TLBO algorithm has been used to optimize the parameters to minimize the SFC in AWSJ machining. To confirm the result CFD Analysis has been performed to obtain the value of SFC for optimized value of parameters. Umang Anand and Joseph Katz [6] demonstrated that the porous lubricated nozzles can substantially reduce the extent of nozzle wear of abrasive water suspension jets. Once several issues associated with commercializing this technology are resolved, it may expand the use and applications of high-speed abrasive water jet cutters. Being able to accelerate the particles to nearly the liquid velocity with minimal damage to the nozzle, even when the nozzle is made of plain stainless steel, is a substantial improvement over other presently used techniques. Compared to the present commercial abrasive water jet ~AWJ cutters, the smaller jet diameter and the lower pressure required to achieve the same cutting effect, may result in cost savings, higher cutting efficiency and more precise cutting. A more durable nozzle may also enable further reduction in nozzle diameter, hence, even greater cutting precision, and higher particle speeds that may lead to deeper cutting. Josef Foldyna et. al [7] concluded that increase in the working pressure results in a slight increase in abrasive particle velocities; increase in the abrasive mass flow rate results in a small decrease in abrasive particle velocities; decrease in the inner diameter of the plastic tube for the delivery of abrasive particles to the AWJ cutting head results in significant increase in abrasive particle velocities; longer plastic tube for the delivery of abrasive particles to the AWJ cutting head has only a minor influence on velocities of abrasive particles.

III. SYSTEM DEVELOPMENT

Knowing the velocity and mass distribution profiles would enable us to calculate the energy profile of the abrasive water jet, which, beside the work piece material properties, is the most important input parameter to modeling the material removal process. Most of the kinetic energy is transported by the high velocity abrasive particles and the water jet. Even if the air flow reaches supersonic velocities, this phase of the abrasive water jet transports just a small amount of the total kinetic energy due to the low density of air. In water jet cutting, the kinetic energy of the water is high enough to remove the work piece material, but in order to machine harder materials; a higher amount of kinetic energy has to be available. This energy can be stored in abrasive particles due to their higher density comparing to the water density. The available energy in the time interval tj, during which an abrasive particle is applied such that the energy is dispersed, which is defined by eq. (1) and to the abrasive particles having the energy in kinetic form, defined by eq. (2),

$$E_{KWJ,i} = \frac{m_{WJ,j} v_{WJ,j}^2}{2} \tag{1}$$

$$E_{KAP,i} = E_{KAp,j}^{T} + E_{KAP,j}^{R} = \frac{m_{AP,j} v_{AP,j}^2}{2} + \frac{J_{AP,j} \omega_{AP,j}^2}{2} \tag{2}$$

As evident from eq. (2), the kinetic energy of abrasive particles is composed by the energy stored in particle translation and energy stored in particle rotation. In the equations (1) and (2), $m_{wj,j}$is the mass of the part of WJ associated to the time interval t_j, $v_{wj,j}$the average velocity of the WJ, while $v_{AP,J}$ is the velocity, $\omega_{AP,j}$ the rotational velocity and $J_{AP,j}$ the inertial momentum of the observed abrasive particle. The modeling of the abrasive water jet machining process is based on few important principles of fluid dynamics and fluid systems. They are Bernoulli's principle (Fig. 3.1), intensifier and mixing chamber. In fluid dynamics, Bernoulli's principle states that for an inviscid, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy. The fundamental principle of the law of conservation of energy is used for an ideal fluid and is as follows:

$$P + \frac{\rho_w v_w}{2} + \rho_w gh = \text{Constant} \tag{3}$$

where, P - water pressure, v_w- velocity of water, ρ_w - density of water, g - acceleration due to gravity and h - height of the observed points above the reference plane. By observing the leakage of high pressure water jets in the air and using equation (3), one can determine the leakage velocity of water jet from a nozzle based on water pressure.

$$P + \frac{\rho_w v_w^2}{2} + \rho_w g h_1 = P_{at} + \frac{\rho_w v_{wj}^2}{2} + \rho_w g h_2 \tag{4}$$

or

$$P - P_{at} = \frac{1}{2} \rho_w (v_{wj}^2 - v_w^2) + \rho_w g (h_2 - h_1) \tag{5}$$

For $P_{at} << P$; $v_{wj} >> v_w$; $h_1 \approx h_2$ (6)

$$P = \frac{1}{2} \rho_w v_{wj}^2 \tag{7}$$

Now, few assumptions are made to simplify the expression into a generalized form. The assumptions are as follows:

- The height difference is fully neglected.
- It is assumed that the speed of the water on nozzle entrance is negligible compared to the speed of the jet at the nozzle exit.
- The atmospheric pressure (1 bar) is much smaller than the water pressure at the entrance to the nozzle (4000 bar).
- Based on these assumptions, the equation for calculating the velocity of the water jet after exiting the water nozzle is obtained as,

$$v_{wj} = \sqrt{\frac{2P}{\rho_w}} \tag{8}$$

The velocity of the water jet thus formed can be estimated, assuming no losses as shown by eq. 8 using Bernoulli's equation where, p is the water pressure and ρ_wis the density of water. The orifices are typically made of sapphire. In commercial machines, the life of the sapphire orifice is typically around 100 – 150 hours. In water jet machining, this high velocity water jet is used for the required application where as in abrasive water jet machining it is directed into the mixing chamber. The mixing chamber (Fig. 3.2) has a typical dimension of inner diameter 6 mm and a length of 10 mm. In this case, the velocity of the water is very high and is issued from the orifice into the mixing chamber. As a result, a low pressure (vacuum) is created within the mixing chamber. By exploiting this principle and making use of the advantage, the metered abrasive particles are introduced into the mixing chamber through a port.

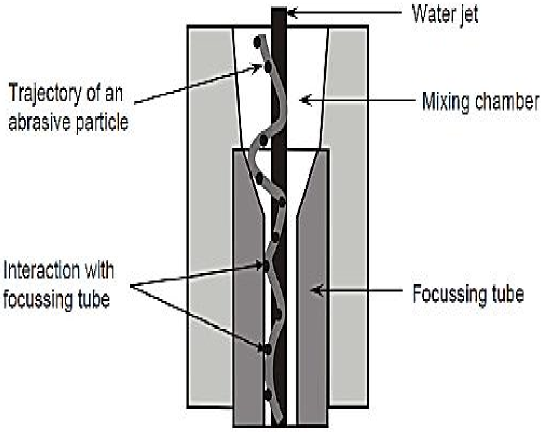

Figure 1. Schematic Diagram of the mixing process

The abrasive particles are introduced within the water jet. Finally, because of this mixing action, the abrasive water jet comes out of the focusing tube as fully developed. It is evident that during the process of mixing, the abrasive particles are gradually accelerated. This is because of the transfer of momentum from the water phase to abrasive phase. Further, the jet lastly leaves the focusing tube, phases, water and abrasive. At this moment, all are expected to be at same velocity. The mixing chamber, as shown in Fig. 3, is immediately followed by the focusing tubeor the inserts. Abrasive particles during mixing try to enter the jet, but they are reflected away due to interplay of buoyancy and drag force. They go on interacting with the jet and the inner walls of the mixing tube, until they are accelerated using the momentum of the water jet. Considering the energy loss through water jet development at the orifice, the water jet velocity is estimated and obtained as given by the expression:

$$v_{wj} = \psi \sqrt{\frac{2P}{\rho_w}} \tag{9}$$

Where, φ is coefficient of velocity =0.96

Assuming water pressure = 470MPa and density = 1000 Kg/m^3 we get,

v_{wj}=930m/s (10)

Stress Analysis of Nozzle

Here three models are generated as shown in fig. 3.3, 3.4 and 3.5 respectively. The stress induced in the nozzle perpendicular to the direction of flow is given by,

$$\sigma_N = K_s \left(\frac{Pd}{4t} \right) \tag{11}$$

Where, σ_N = Stress in Nozzle, K_s = Shape Factor (1.7 for Model 1 and 2, and 1.5 for model 3), P= Water Pressure, d = Dia. Of nozzle, t= nozzle thickness.

As we know the stress in nozzle we can find out strains in nozzle.

Because, $$\sigma_N = E\epsilon \tag{12}$$

And the deformation is given by,

$$\text{Deformation} = L\epsilon \tag{13}$$

Where, L is Taper Length of nozzle.

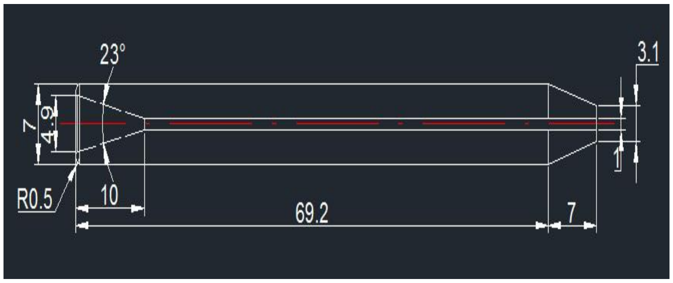

Figure 2. Model 1 of Nozzle

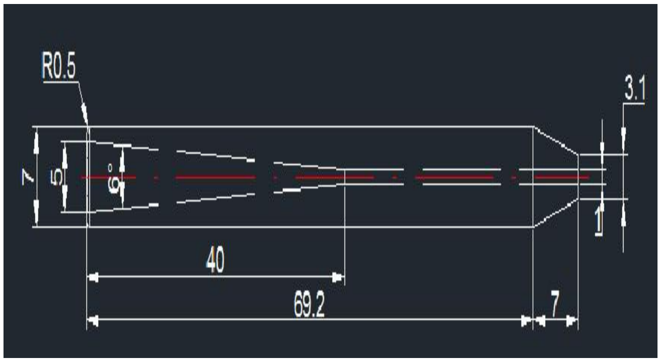

Figure 3. Model 2 of Nozzle

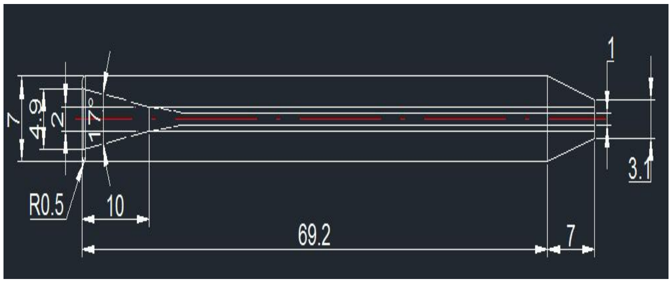

Figure 4. Model 3 of Nozzle

IV. RESULTS AND DISCUSSIONS

The three types of nozzles are adopted for the analysis. Model 1 is of ordinary design from market survey. Model 2 is adopted by changing taper length of ordinary nozzle while model 3 is adopted by ceramic coating inside the nozzle of 1 mm thickness. The models are designed in CATIA V5R16 and then imported in ANSYS workbench for finite element analysis.

The results of ANSYS for all the models are shown in fig. below.

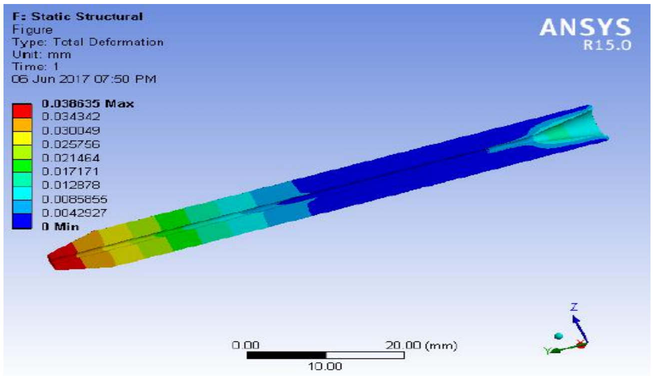

Figure 5. Total Deformation for Model 1

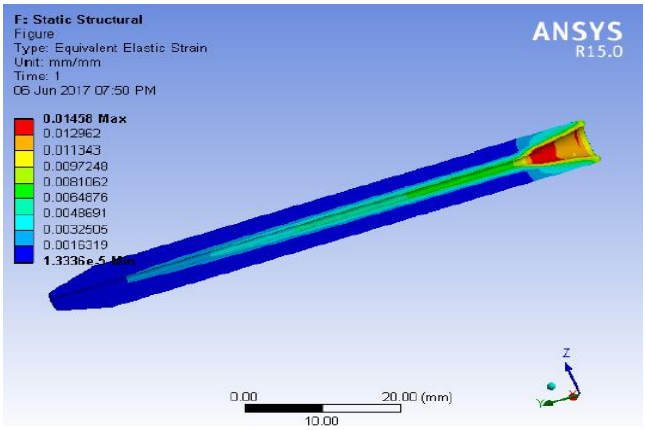

Figure 6. Elastic Strain for Model 1

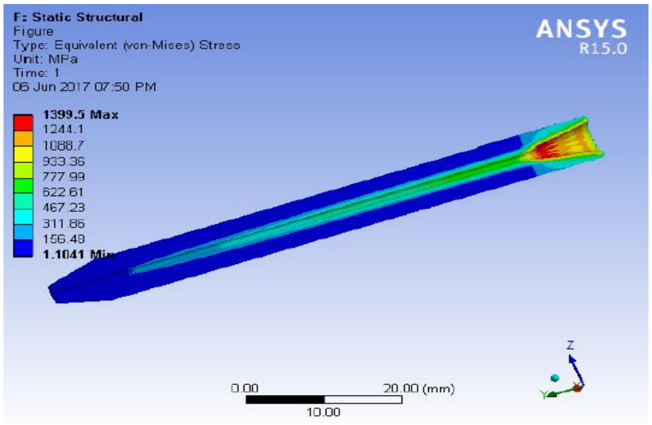

Figure 7. Von-miss Stress for Model 1

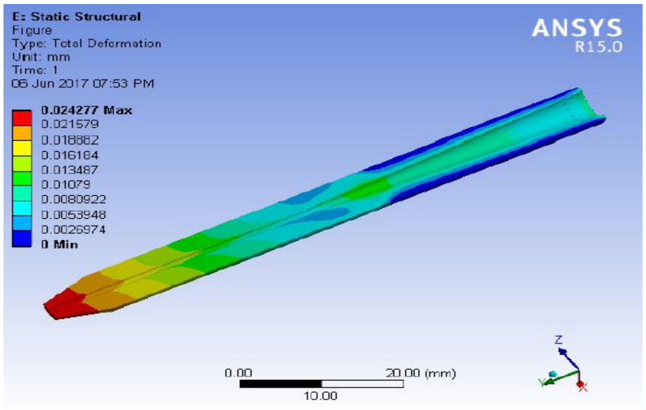

Figure 8. Total Deformation for Model 2

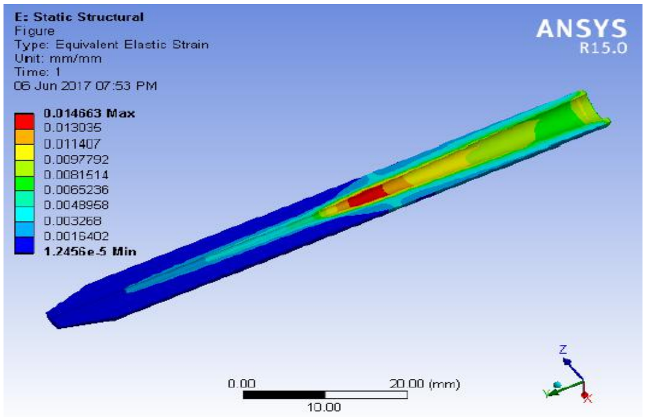

Figure 9. Elastic Strain for Model 2

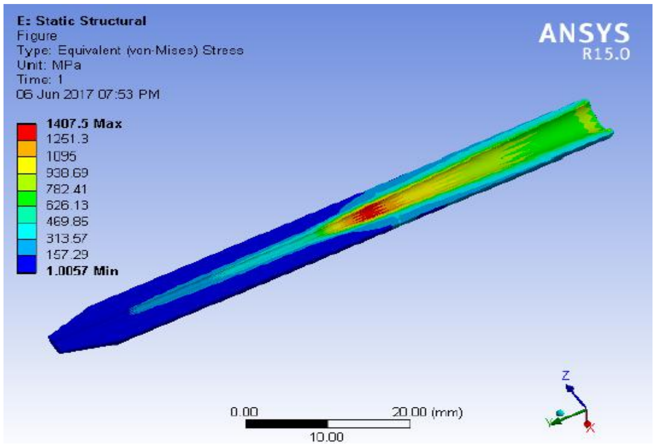

Figure 10. Von-miss Stress for Model 2

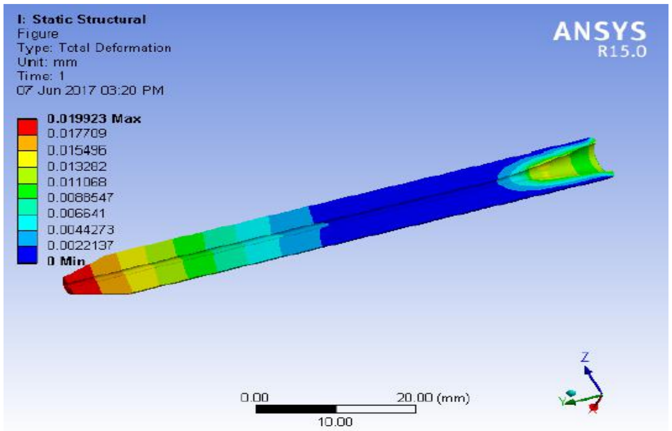

Figure 11. Total Deformation for Model 3

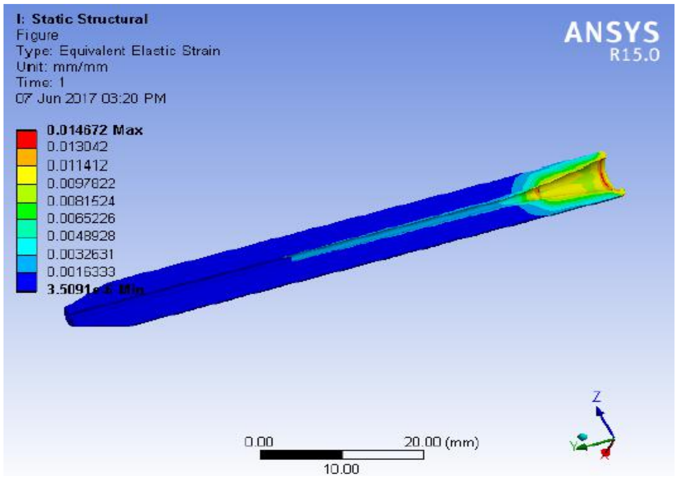

Figure 12. Elastic Strain for Model 3

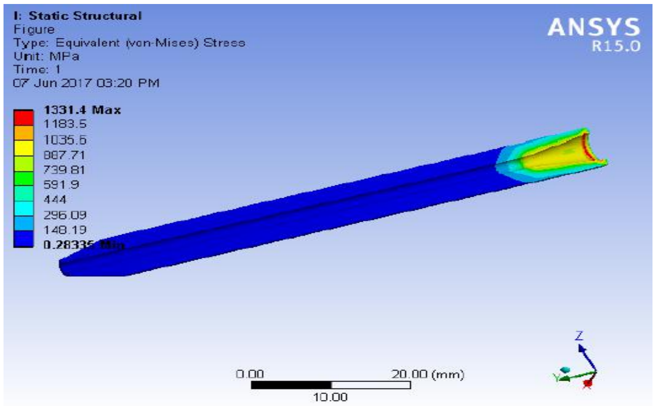

Figure 13. Von-miss Stress for Model 3

By considering von-miss stress, it is difficult to optimize the design. Because model 1 holds good characteristics analytical and ANSYS. However, model 3 is also suitable design among these designs, since it has properties nearly equal by analytical and ANSYS. Also due to presence of coating, the properties may be slightly changed. Thus the optimum design among the models is the model 3 having stress 1331.4 MPa, strain 0.0146 mm/mm and deformation 0.019 mm.

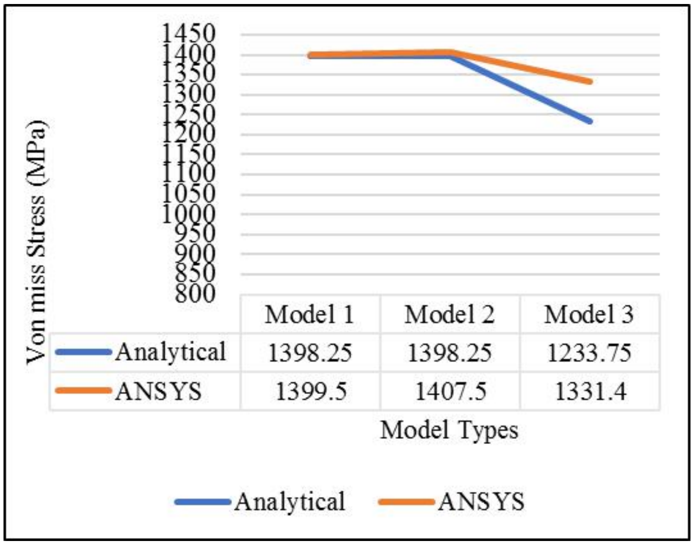

Figure 14. Comparison of Von-Miss Stress for Models

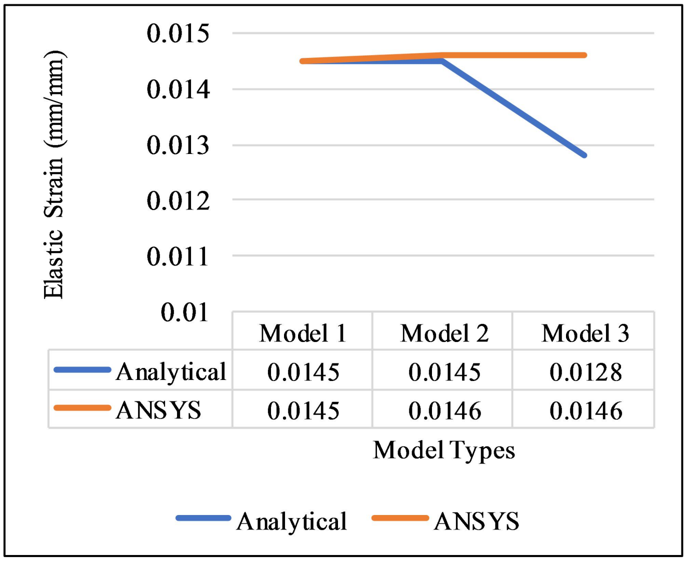

Figure 15. Comparison of Elastic Strains for Models

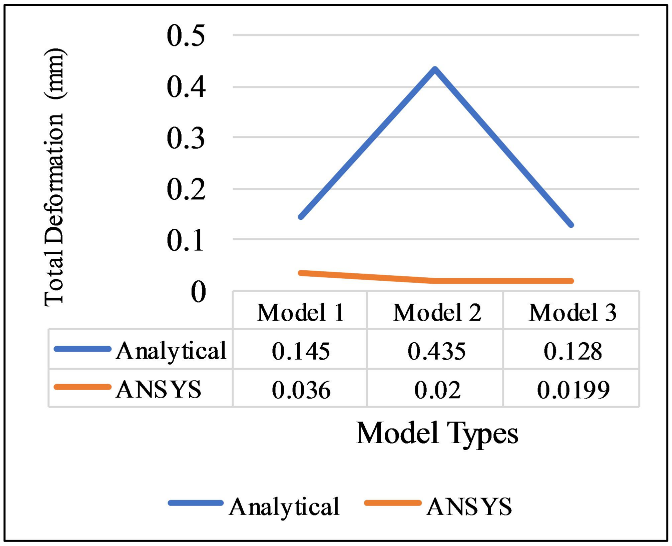

Figure 16. Comparison of Total Deformation for Model

V. CONCLUSION

The present paper shows the design and static as well as CFD analysis of nozzle used in AWJM. Nozzle is one of the important elements of AWJM system. Since it converts pressure energy to required momentum for erosion of particles. Thus it is required to design the nozzle under static and fluid flow. The model 3 is more optimum model among the remaining two models, since it has coating of 1 mm thickness which improves the characteristics of the nozzle.

REFERENCES

[1] M.G. Mostofa, K. Yong Kil, A. J. Hwan, “Computational fluid analysis of abrasive waterjet cutting head, Journal of Mechanical Science and Technology”,24 (2010) 249-252.

[2] M. Rajyalakshmi, P. Suresh Babu, “Abrasive Water Jet Machining - A Review on Current Development International Journal of Science Technology & Engineering”, Volume 2 Issue 12 June 2016.

[3] Saurabh Verma, Dr.S.K.Moulick, Mr.Santosh Kumar Mishra, “Nozzle Wear Parameter in Water jet machining - The Review”, Volume 2, Issue 1.

[4] Deepak. D, Anjaiah D and Yagnesh Sharma, “Numerical analysis of flow through abrasive water suspension jet: the effect of abrasive grain size and jet diameter ratio on wall shear”, International Journal of Earth Sciences and Engineering, Vol. 04, no 04 spl, pp. 78-83, ISSN 0974-5904.

[5] Rakesh Kumar Sahu, Saurabh Verma, Santosh Kumar Mishra, “Optimization Of Parameters To Minimize The Skin Friction Coefficient In Abrasive Water Suspension Jet Machining Through Tlbo”, Technical Reasearch Organization India, Volume-1,Issue-4,2015.

[6] U. Anand and J. Katz, “Prevention of nozzle wear Abrasive Water Suspension Jets (AWSJ) using porous lubricated nozzles”, Journal of Tribology, vol. 125, no. 1, pp. 168–180, 2003.

[7] Josef Foldyna, Michal Zelenak, Jiri Klich, Petr Hlavacek, Libor Sitek, Zdenek Riha, “The Measurement Of The Velocity Of Abrasive Particles At The Suction Part Of The Cutting Head”, Technical Gazette, Vol.22 No.6, December 2015.

[8] M. Hashish, “Observation of wear of abrasive-waterjet nozzle materials”, Journal of Tribology 116 (1994) 439-

444.

[9] M. Nanduri, D. G. Taggart, and T. J. Kim, "The effects of system and geometric parameters on abrasive water jet nozzle wear", International Journal ofMachine Tools andManufacture, vol. 42, no. 5, pp. 615–623, 2002.