CFD Modeling and Optimization of Magneto-rheological Abrasive Flow Finishing (MRAFF) Process

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Abstract:- A modern nano finishing technique called magnetorheological abrasive flow finishing (MRAFF), which is simply a combined hybrid form of abrasive flow machining (AFM) process and magnetorheological finishing (MRF) process, has been designed for micro finishing of parts even with difficult geometry for a broad range of industrial purposes. In the present work, a model for the prediction of removal of material and surface roughness has been estimated. An effort has been made to study the flow passing through the stainless steel workpiece by CFD modeling in ANSYS 15.0 FLUENT. By assuming the medium as Bingham plastic various parameters affecting the surface roughness has been calculated. Also a theoretical calculation is made for the model if no magnetic field is applied and then comparative study of the two models is proposed. An optimization of the process has also been carried out. With the help of SN Ratio plot and Means plot optimized value of input parameters has been found out to achieve better surface finish.

Key words : Geometry, Nano, Magnetorhelogical, Stainless steel, magnetic field, Bingham plastic

Introduction : 1.1 Preamble

The available advanced and traditional concluding processes alone are incompetent of producing anticipated surface characteristics on complex geometries and in exercising in-process control on ultimate action. Precision finishing of complex geometries and internal surfaces is always of anxiety being labor intensive and challenging to control. In the contemporary technological world numerous products need a surface roughness of the order of a nanometer (10^{-9} m). It is preferable to use automate the technique where the desired surface finish can be achieved as a function of time. To obtain desired geometrical precision and surface characteristics by removal of unwanted superfluous material from the workpiece surface, small multiple cutting edges of abrasives are usually used. All traditional finishing routes *viz.* lapping, grinding, honing, etc. work on this mechanism of finishing.

1.2 Overview of Magnetorhelogical and Allied Finishing Processes

The available traditional processes are unable of producing desired nano/micro level finishing also these require high expensive equipment, more time consuming and economically incompetent. Magnetorheological Abrasive flow finishing is one of the processes with wide range of application. Before going into the detail discussion of MRAFF process let first discuss other processes i.e. MAF, MRF and MFP were the control of performance is done by the use of magnetic field. In these processes, the force acting on the work piece surface through the abrasive particles is controlled externally by changing the magnetic flux density.

1.2.1 Magnetic Abrasive Finishing (MAF)

In this technique, basically ferromagnetic particles are sintered with fine abrasive grains (Al_2O_3, SiC, CBN, or diamond), and those particles are known as ferromagnetic abrasive particles (or magnetic abrasive particles). Fig. 1.1 shows a schematic figure of a plane MAF technique which has the power to control the finishing process is by controlling the application of magnetic field across the machining gap among the top surface of workpiece material and bottom surface of the electromagnet pole which is rotating.

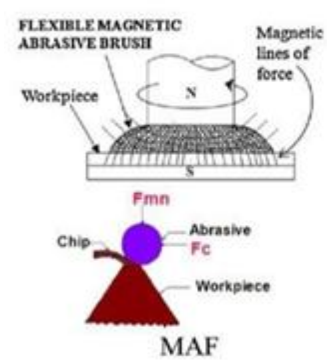

Fig. 1.1 Magnetic abrasive flow machining

1.2.2 Magneto-Rheological Finishing (MRF)

C entre of Optics Manufacturing at Rochester, has designed a process to automate the lens polishing process known as Magnetorheological Finishing (MRF), which relies on a unique "smart fluid", known as Magnetorheological (MR) fluid. Magnetorheological fluids are suspensions of nano-sized magnetizable grains such as carbonyl iron particles (CIP), dispersed in a non-magnetic carrier medium such as mineral oil or water. When no magnetic field is applied, an ideal magnetorheological fluid shows Newtonian characteristics. Magnetorheological effect is seen when external magnetic field is applied to the magnetorheological fluid. This process is used for finishing optical glasses, glass ceramics and some non-magnetic metals.

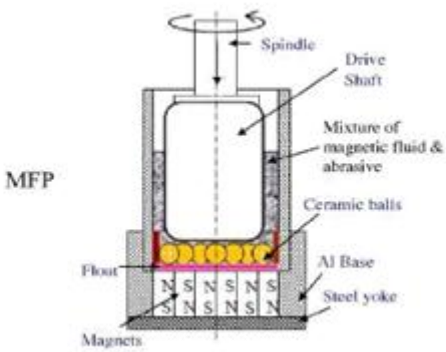

Fig. 1.2 Magnetic Rheological finishing

1.2.3 Magneto Float Polishing

Polishing of spherical surfaces is evenly necessary for which the other two discussed techniques do not meet the criteria. The Magnetic Float Polishing technique has been designed to meet this goals. This process is based on the ferro-hydrodynamic characteristics of magnetic fluid that levitates a non-magnetic float and suspended abrasive particles in it when a magnetic field is applied. The levitation force applied by the abrasives is proportional to the magnetic field gradient which is extremely less and very much adjustable. Magneto float polishing can be a very economic and justified method for nano finishing of brittle materials with spherical and flat shapes. A bank of electromagnets is placed under the finishing chamber.

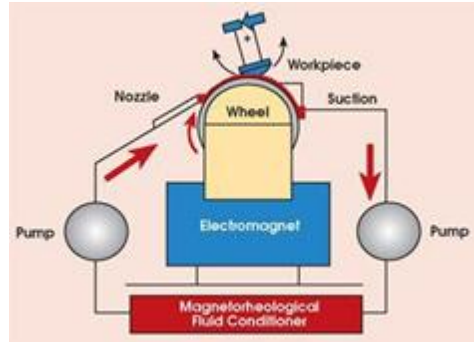

Fig. 1.3 Magneto rheological flow polishing

1.3 Magneto-rheological Abrasive Flow Finishing Process

The process of MRAFF consists of a slug that is magnetized and stiffed with MRP fluid and is flow into and fro through the work piece formed passage. The process of abrasion happens only when a magnetic field is applied on the workpiece, while the other areas are getting unaltered. Fig. 1.4a shows the process. The rheological action of polishing changes with the change in the behavior of the fluid from Bingham to Newtonian plastic and the reverse can also occur when entering and exiting the zone of finishing, (Fig. 1.4b).

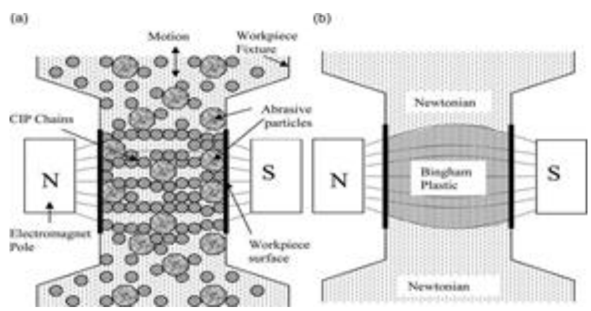

Fig. 1.4(a) MR-abrasive flow finishing mechanism; (b) Change in rheological behaviour of MR-polishing fluid during finishing

In the process of MRAFF, MRPF is passed through the passage of the workpiece that has to finish applying two cylinders that are opposed by a magnetic field applied externally. The smart magnetorheological viscosity of the fluid (MRPF) that will polish the surface is dependent on the magnetic field strength and the required characteristics of finishing. The Bingham plastic fluid used for polishing shears in an area neighboring the surface of the workpiece. This also enhances removal of the material at a higher rate and thus affects the finishing process. The MRP-fluid extruded through the end to end hollow connection that has been formed on the fixture of the workpiece has been achieved by running two pistons in MRPF cylinders that are opposed using pressure actuators by hydraulic mode

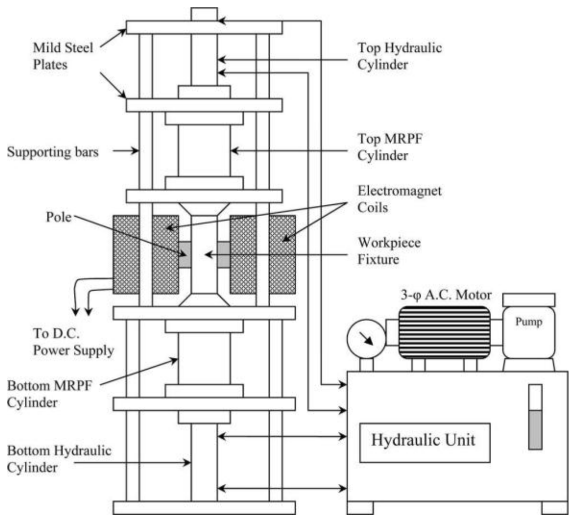

Fig. 1.5 Schematic diagram of the MRAFF setup

1.4 Magnetorheological polishing (MRP) fluid

Rabinow invented the magnetorheological (MR) fluid at the end of the 1940-50 decade. They are considered as part of the distinguished controllable materials. The rheological properties of these smart materials can be externally modified by the applying some field of energy. Magneto-rheological-fluids are sols of magnetized particles *viz.*, carbonyl iron, in a non-magnetic emulsion carrier medium *viz.*, oil of silicone, or other mineral or water. The nonappearance of magnetic field causes an ideal magnetorheological-fluid to display Newtonian behavior and on the applying a magnetic field externally, the fluid shows an MR-effect. When we apply a magnetic field, the particles exhibiting magnetic properties inside a non-magnetic fluid carrier accomplish dipole moments that are directly dependent on the field of magnetic strength. The particles that tend to exhibit magnetic properties accumulate into links of dipole moments that are assigned to the direction of the applied field when the dipolar interface in between the particles surpasses their thermal limit of energy. Since energy is absorbed to deform and break these chains, the change in the microstructure is accountable for the commencement of the large finite stress due to the yield that is also controllable. When the fluid is deformed under stress, the chains tend to distort in the direction of applied strain and break when the stresses that are applied go beyond their yield stress induced by field. The particles again rearrange in their random state and the fluid displays their real Newtonian behavior as the field externally applied is removed. When the stress applied onto the linked structure of the magnetorheological-fluid within the existence of field applied, they are modeled as plastic fluid exhibiting Bingham characteristics with the dependence of field with yield stress that can be explained mathematically by the following:

$$\tau = \tau_0(H) + \eta$$

$$\tau = 0 \quad \text{for } \tau<\tau_0$$

where τ is the shear stress that has been applied, is the rate of shear, η is the dynamic viscosity found from the composition of the base fluid and the magnetic field-induced shear stress. As a result, it depends significantly on the strength of the applied magnetic field, H. The fluid strength is enhanced when the magnetic field applied is increased. However, the enhancement is not linear in behavior as the particles behave ferro-magnetically and the degree of magnetization at different locations of particle take place in a non-uniform manner. Magneto-rheological fluids conventionally display a yield strength of 50–100 kPa (dynamic) under the influence of a magnetic field of strength 150–250 kA/m. The ultimate strength of magneto-rheological-fluid is restricted by the saturation of magnetic influence. The flexibility to electrically modify the rheological behavior of the magneto-rheological-fluid attracts a wide consideration from a varied class of industries as well as multiple applications are too explored. MRP fluid consists of magneto-rheological-fluid having abrasive particles with finer dimensions and dispersed as grains. After applying a magnetic field, the carbonyl iron particles (CIPs) form a continuous link-like structure having columnar assembly and the abrasives being implanted in between. The magneto-force that acts in between the iron grains surrounding abrasive particles provides a bond-strength to it. The scale of the force is dependent on the concentration of iron, applied field intensity of the magnet, magnetic permeability of grains and the particle size.

2. SIMULATION OF MRAFF

CFD is a computational technique used in engineering to analyze complex real life problems. CFD uses numerical discitization techniques to obtain approximate solutions. The exsactness of the obtained approximate solution depend on the no. of discritization of the phisical domain and the truncation accuracy used for solving the problem.CFD has become feasible due to the advent of high speed digital computers. CFD uses continuum mechanics, hence solves an system of coupled differential equation numerically.

2.1 Advantages of CFD over experiments

The benifits of CFD over experiments are discussed below –

- CFD simulation experiments can be conduct complex problems which may be difficult or outright immposible to achive experimentally. Also, hazards involving the experimentation is avoided.
- CFD is a nondistructive test so it‟s a very cost effective method. In many problems, such as optimization, fine tuening of many parameters is required. To study such problems experimentally it be required to model prototypes for each parametric optimization carried out. So cost of such eperiment will rise exponentially. Hence, it is always advisible to opt for CFD based solution.
- Simulation-based design instead of "build & test".CFD provides high-fidelity database for diagnosing flow field.CFD provides exact and detailed information about HVAC design parameters: CFD gives broader and more detailed information about the flow within an occupied zone, and meets this goal better than any other method.
- CFD is more consistent because the simulation schemes and methods upon which CFD is based are improving rapidly. Also using normal programming software such as C, frotron and matlab it is posible to design solver based on the complex physics associated with the problem hence yielding a more real life solution. Final experimental testing of an approved CFD model can be conducted to check for its consistency.

2.2 Application of CFD

For the benefits discussed above now a days it has seen that CFD is been used in various fields. Some of the area discussed here -

In validation/optimization of HVAC design parameters

CFD analysis is done to validate many design aspects such as exhaust temperature , flow rate, location and no. of diffuser and exhausts.So it is seen that all the design criteria can be finely tuned using CFD analysis

In modification/improvement of malfunctioning HVAC systems:

With the use of robust CFD solver, it is possibe to get solution depending on application. Also fault analysis of the system under study can be achived hecnce, dectecting malfuntions.

In comparisons between alternative systems:

For cirtain design layout, there exsists severa methodology for designing HVAC systems for a space. As stated earier, CFD application can improve design and also be able in comparing different design, thus yielding a better altenative system.

In an engineering investigation:

CFD analysis of of many control variable such as pressure, temperature chemical concentration gives new insigh in understanding complex procedures. It also helps engineers and scientist make proper decision.

2.3 Modeling

Modeling is the art of converting a physical problem into the language of mathematics. In doing so many assumtions are made reducing the complexity of the problem. But, it is very important to preserv the basic physics of the problem while appling the assumption as it may lead to very unrealistic solutions

2.4 How does CFD work

CFD packages comprise sophisticated user boundaries inputproblem parameters and to inspect the results.Hence all codes comprise three main elements -

1. Pre-processor
2. Solver
3. Post - processor

2.4.1Pre-Processor

Pre-processor consists of the input of a flow problem to a CFD program by means of an operator-friendly interface and the subsequent transformation of this input into a form suitable for use by the solver. Pre processing stage involves fixing the domain, Generation of grids, Selection of physical and chemical phenomena, Definition of fluid properties, and Specification of appropriate boundary conditions. Following are the user activities –

- define geometry & generate grid
- selection of phenomena to be modeled
- definition of fluid properties
- specification of boundary and initial conditions

2.4.2 Solver

Three primary numerical solution techniquesfinite difference, finite element and finite control volume. In outline the numerical methods that form the basis of solver. The numerical method done by the following:

- Approximates the unknown variables by simple functions
- Discretization by substitution of the approx-imations into the governing flow equations and subsequent mathematical manipulations
- Solution of the algebraic equations

2.5 Present Study

In the current study a 2D computational fluid dynamics (CFD)simulation of the medium along the workpiece fixture has been carried out in ANSYS 15 FLUENT to calculate the axial stress, radial stress and depth of indentation to find out the volumetric material removal rate. Also a calculation has been made to find out the surface roughness to examine the level of precision that can be achived by this finishing process.

2.5.1 Govering Equations

The mathematical depiction of the flow of magnetorheological polishing fluid in Magnetorheologial abrasive flow finishing process involves general equations of continuity and momentum. At first the basic equation of continuity and then the z-component of momentum equation in cylindrical coordinate system are solved. For Bingham plastic fluid, relation between viscosity and shear rate (μ = *f* (x)) which is a nonlinear function. For the present work, viscosity is not justdepends on shear rate althougha function of the applied magnetic effect through τ_y. Thus, it is a bit difficult to solve the analytical solution of Navier– Stokes equation and therefor CFD simulation is carried out.

Following are the assumptions used tomake simplier the analysis work:

- The medium is taken as homogeneous, isotropic and incompressible in nature.
- The flow is sassumed as a steady and axi-symmetric flow
- A fully developed flow is assumed (i.e. $v_r = 0$, $dv_z/dz = 0$) with no spin (= 0)
- $\tau_{rz} = \mu(dv_z/dr)$

After applying the above assumptions the final form of the continuity and z-component of the momentum equation is summarised as

$$-\frac{dp}{dz} + \frac{z}{r}\frac{dv_{z^-}}{dr} + \mu\frac{d^2 v_z}{dr^2} + \frac{dz}{dr}\frac{dv_{z^-}}{dr} + \rho g_z = 0$$

where vz and vr are z and r components of the velocity. $\delta p/\delta z$ is pressure gradient in the z direction and it is obvious to change linearly from inletsto exitsof the computationalszone, and it is determined as $\delta p/\delta z = -(P_{applied} - P_{friction})/L$. Here, $P_{frictions}$ is the loss of pressure because of the piston friction and insthe currentstudy it is taken as equivalent to 15 bar. $P_{applied}$ here is the pressures applied by the pumps and L is taken as the length of fixture.

3. RESULT AND DISCUSSION :

Simulation results of the fluid flow through the workpiece fixture is analyzed. Then calculation is made to find the numerous parameters like total normal force, shear force, indentation depth and material removal from the analysis data.

3.1 Velocity Distribution

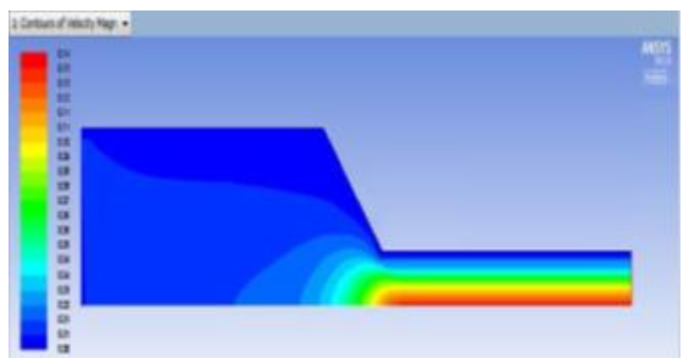

Fig. 3.1 Velocity distribution along the workpiece fixture

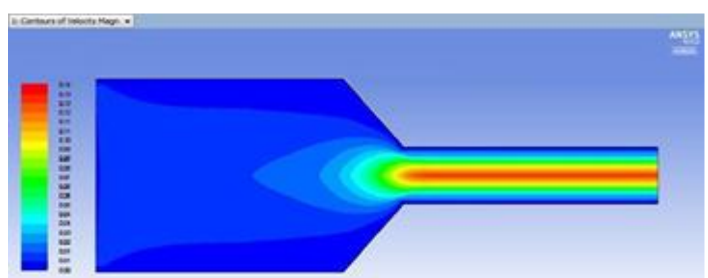

Fig. 3.2 Velocity distribution on full view of work piece fixture

Reference to the Fig. 3.1,3.2 we can conclude that the velocity changes when it reaches the taper exit, magnitude of velocity is maximum at the centre and decreases gradually towards the wall, because the effect of high viscosity present in the media.

3.2 Pressure Distribution

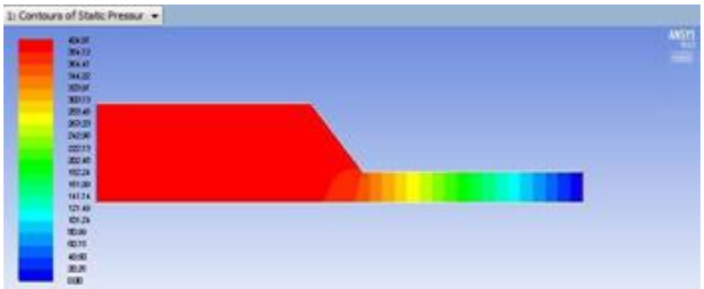

Fig. 3.3Pressure distribution along the workpiece fixture

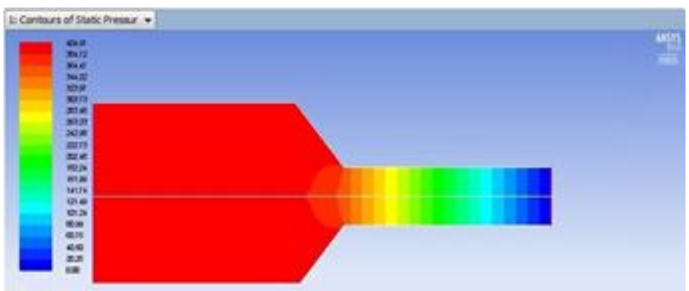

Fig. 3.4Pressure distribution on full view of work piece fixture

Reference to the Fig. 3.3,3.4 it is seen that the pressure distribution in the region of work piece fixture remains constant upto theexit of the taper. After that it decreases gradually to the end of the workpiece.

3.3 Strain Rate Distribution

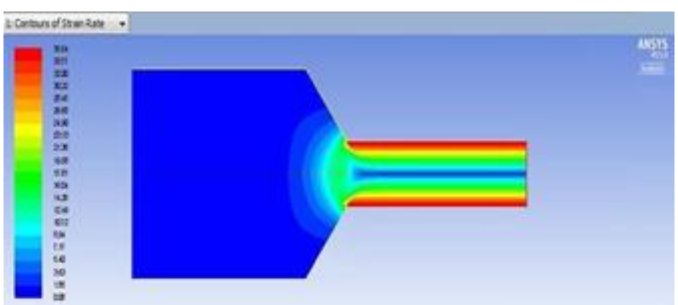

Fig. 3.5Strain distribution along the workpiece fixture

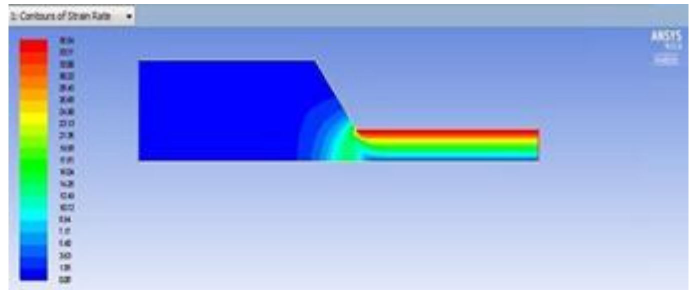

Fig. 3.6 Strain distribution of full view of work piece fixture

Reference to the Fig.3.5,3.6 we can conclude that the strain is maximum at the wall. That‟s why stress will be produced there to remove the material.

3.3.1 Plot of axial wall shear stress with position

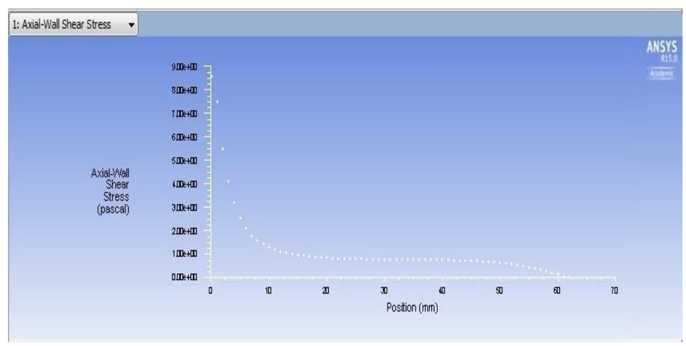

Fig. 3.7 Axial wall shear stress with position

3.3.2 Plot of radial wall shear stress

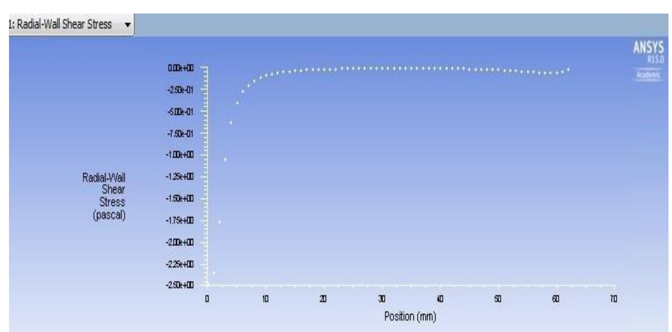

Fig. 3.8 Radial wall shear stress with position

Reference to the Fig. 3.7,3.8 the axial and radial stress can be obtained from the graph and are used for further calculation.

3.3.3 Calculation

From CFD calculation the radial stress on the work piece material it is found as

σ_{rad} = 0.0607106 Pa

So, we got the total indentation force

$$F_N = 4.167 \text{ X } 10^{-10} \text{ N}$$

Now the indentation diameter can be calculated by putting the value of F_N in equation

$$D_i = 4.106 \text{ X } 10^{-8} \text{ m}$$

Now we get depth of indentation,

$$t = 1.041 \text{ X } 10^{-10} \text{ m}$$

Then projected area can be calculated as,

$$A" = 3.604 \text{ X}10^{-20} \text{ m}^2$$

Now F_{shear} and F_R are given as,

F_{shear} = (A- A") x shear stress of the field

and F_R= A" x σ_{yps}

where,

σ_{yps} = yield point stress of stainless steel workpiece = 540.30 MPa

Now we obtained F_{shear} and F_R as 1.89 x10^{-6} N and 4.71x10^{-11} N.

As we see F_{shear} > F_R. So material removal should happen on the workpiece surface.

Surface roughness has also been calculated for 200 cycles (*i* = 200) and found as 0.43µm.

4.3.4 Validation with Experimental Results

- From previous experimental data it is found that F_{shear} and F_R value is 1.25 x 10^{-5} and 2.76 x 10^{-10} respectively. So we can say that the model is validated.
- Surface roughness has also been calculated for 200 cycles and found as 0.43µm. From previous paper it is seen that R_a value is calculated as 0.34µm. So we can say that the prediction is correct.

4.3.4 A new model when no magnetic field is applied

The calculation is also made for no magnetic effect and then the results are compared with the actual modeling.

As the magnetic effect is neglected. So in the calculation for total normal force F_N ,the magnetic component F_m is omitted and then the corresponding calculation is made without changing the other formulaes.

The value we got as,

$F_N = 3.43 \text{ x } 10^{-12}$

$F_{shear} = 4.18 \text{ x } 10^{-8}$ and $F_R = 4.71 \text{ x } 10^{-11}$.

- As we see here F_{shear}> F_R. So removal of material should undergo on the workpiece. But as the normal force acting on the abrasive is so less so there is not such improvement in surface finish and surface rouhness found as 0.11 µm

4. Conclusions

Based on the theoretical investigationobtainable from this study, subsequent conclusions have been developed

- From the CFD analysis it is validated with the theoretical model that shearing is happening during finishing, when applied shear force applied on the abrasive particle is more than the workpiece material"s resisting force due to the strength of the material and it is the main cause of material removal.
- From the results obtained from the CFD analysis it can be concluded that the model predicts nano level finishing and model data is validated with available experimental results.
- When no magnetic effect is applied CIPs don"t get that required bonding force corresponding to that the normal force is less which is required to indent the abrasive particle. So surface roughness achieved is less but material removal will occur as shear force is greater than reaction force.
  - It is concluded that for optimizing the finishing process it is required that the value of axial stress and indentation depth should be low and value of radial stress should be high. The conclusions from the optimization made are following:

- The optimum process parameters for minimizing axial stress are 0.3T magnetic density, 45 bar inlet pressure and 0.01 m/sec inlet velocity.
- The optimum process parameters for maximizing radial stress are 0.3T magnetic density, 45 bar inlet pressure and 0.03 m/sec inlet velocity.
- The optimum process parameters for minimizing indentation depth are 0.3T magnetic density, 37.5 bar inlet pressure and 0.01 m/sec inlet velocity.

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