Thermal Analysis of Ball End Magnetorheological Finishing Process

A

Dissertation

Submitted in partial fulfillment of requirements for the award of degree of

Master of engineering (M.E.)

In

Thermal Engineering

Submitted By

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JULY 2015

CERTIFICATE

I hereby declare that the seminar report entitled **"Thermal Analysis of Ball End Magnetorheological Finishing Process"** is an authentic record of my own work carried out as requirement for the award of Master of Technology in **Thermal Engineering** at Thapar University, Patiala under the guidance of D**r. Anant Kumar Singh,** (**Assistant Professor**, **MED**) during August to July., 2015. The matter embodied in this report has not been submitted in partial or full to any other university or institute for the award of any degree.

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ACKNOWLEDGEMENT

At first, my heartfelt thanks to the almighty for his abundant blessing showered on me throughout this Endeavour to complete the thesis work successfully. I am thankful to my parents and shyna arora for their great support throughout my life. I would cherish every moment where my parents were so keen and curious to know about the details and progress of my work, which boosted my confidence. I express my deep sense of gratitude to them.

My honorable guide **Dr. Anant Kumar Singh**, Assistant Professor, Mechanical Engineering Department, is a person to whom I shall always remain grateful for his excellent guidance, valuable discussions, encouragement, constructive criticism and his insights have strengthened this study significantly. He gave me a complete freedom to use my opinion, correcting whenever necessary in my dissertation.

I would like to thank our Head of the Department, **Dr. S.K. Mohapatra**, who has been supportive at all times and accommodative.

Manish kinger

ABSTRACT

Thermal analysis on ball end magnetorheological finishing tool has been done to find the tool tip temperature at various magnetizing currents. The magnetorheological polishing fluid is used as a finishing medium and it retained strongly at the tool tip surface during the finishing operation under the influence of magnetic field. The viscosity of magnetorheological polishing fluid starts decreasing as temperature increases above 50ºC. The performance of the finishing process also start decreasing as bonding strength of magnetorheological fluid decreases above the temperature of 50ºC to finish the work surfaces. Therefore thermal analysis has been done to know the tool tip surface temperature at various heating conditions with magnetizing currents.The thermal analysis has been done at the magnetizing currents 1 to 7A theoretically and practically at 1 to 4A. It has been determined that the tip temperature approximately same calculated by theoretically and practically. During thermal analysis the tip temperature goes above 50ºC by passing current, By maintaining the coolant temperature it has been found that the temperature at the tip goes below 50ºC.

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ABBREVATIONS

MRF	Magnetorheological finishing
SEM	Scanning electron microscope
OM	Optical microscopy
HEFJ	High energy fluid jet machining
MRAH	Magnetorheological abrasive honing
CNC	Computer numeric control
MCF	Magnetic compound fluid
MRAFF	Magnetorheological abrasive flow finishing
FEA	Finite element analysis
CIPs	Carbonyl iron particles

NOMENCLATURE

Symbol	Description
Ra	Surface roughness
Ra_i	Initial surface roughness
Ra_f	Final surface roughness
μ	Viscosity(dyne s/cm^2)
M	Magnetization of magnetic field
μo	Permeability of free space
VH	Gradient of magnetic field
C	CIPs
A	Abrasive
G	Working gap
S	Wheel rotation
F	Magnetic flux density(W/m^2)
r	Radius(mm)
F_n	Normal force(N/m^2)
F_t	Shear force(N/m^2)
F_f	Finishing force
F_{req}	Force req. to remove material
A_p	Projected area of penetration(mm^2)
H	Magnetic field strength (A/m)
R_a	Centre line average roughness value (lm)
c	Strain(dl/l)
g	Viscosity at zero magnetic field (Pa s)
K	Thermal conductivity (W/m^2 K)

CHAPTER 1

INTRODUCTION

Magnetorheological fluid is like a smart fluid in a carrier fluid is a like a oil. When magnetic field on electromagnet coil has been applied on a coil or any substance then the viscosity of magnetorheological fluid increases and then after that it become a viscoelastic fluid. The yield stress developed in a magnetorheological fluid and it is controlled by magnetic field intensity. Then the fluid ability of the magnetorheological fluid transmits the forces and these forces controlled by electromagnet and after that it forms control based applications. (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

Magnetorheological Fluid is completely different from ferro fluid which has smaller paticles. Magnetorheological Fluids is in a manometer scale and it is too dense for Brownian motion. Ferro fluids are like nano particles which is a brownian motion and does not settle under a normal conditions. Magnetorheological fluids and ferro fluids are too different fluids and these two fluids have different applications. (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

In magnetorheological fluid modelled of large scale abrasion on superfinish grinding. Shift lever force and shift ability arc are the two important design consideration. The tool used was soft coated tool. The basic idea in this modelling was higher the height of the peak lower the probability.i this modelling it provides morphology of initial surface. It tells how the process superfinishing for morphology functions[2]. In magnetorheological fluid we studied of tribological performance of smart fluids and magnetorheological fluids with steel-steel point contacts. The results we studied was lower friction and wear damage which was done by optical microscopy and scanning electron microscopy. It also studied for evaluate lubricating properties.[3]. Magnetorheological fluid also studied high precision positioning with smart fluids as an active medium. In this process we studied high precision, gripping and handling operations of light objects.[4]. Another study done was stagnation effect of glass with abrasive water jet machining. In this MR fluid presented crack free machining with computational fluid mechanics(CFD) which was controlled by stagnation under the jet and horizontal flow. It changes the flow direction and high fluid velocities[5]. For generating complex parts or advanced parts by high energy fluid jet machining. In high energy fluid jet machining it was difficult cutting materials[6]. In magnetorheological finishing process also developed finishing flat and 3D workpieces by finishing tool used. In this MR finishing processs observed variation in magnetic normal force[7].

1.2 How it works

The magnetic particles are show in diagram as Fig 1.1, these are like micrometer scale or in a nanometer scale and these particles are suspended in a carrier fluid which is a type of oil and these particles are distributed randomaly and suspension under some conditions. (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

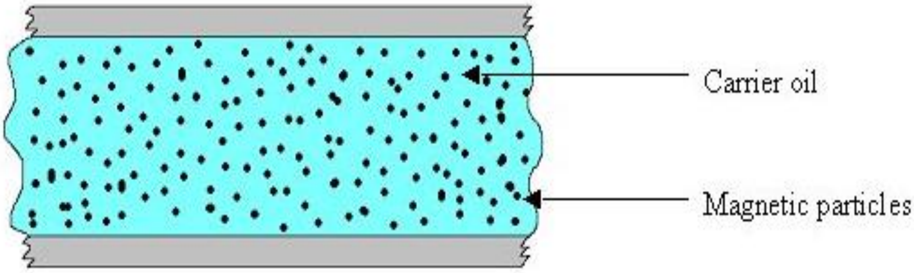

Figure 1.1:Magnetorheological fluid with magnetic particles

(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

This applied magnetic field in a magnetorheological fluid like a microscopic particles in a carrier fluid which have a range of 0.1 - 10um and this range has an alignment of in the lines of magnetic flux (http://kn wikipedia.org/wiki/Magnetorheological fluid).[1]

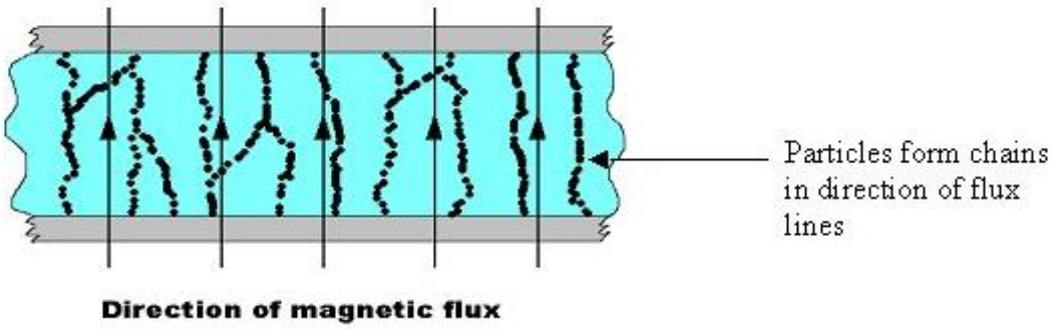

Figure 1.2:Magnetorheological fluid with Magnetic Field

(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

1.3 Material behaviour of Magnetorheological fluid

To understand the behaviour of magnnetorheological fluid you need to make a model of magnetorheological fluid which is fluid mathematically which is very complicated to make a model under some material properties. Magnetorheological fuids are like smart fluids which has low viscosity in the absence of magnetic field is like a quasistatic fluid with some applications. In the case of magnetorheological fluids we assumed some properties and then after assuming we compared it to the solid when it is in active state . When it is active state yield stress increase. The yield stress of MR Fluid is dependable on the magnetic fluid and after applying it to the magnetic field it reach maximum point .It reach maximum point after the increase in magnetic flux density which does not get any effect on the magnetorheological fluid and it is magnetically saturated. The behaviour of magnetorheological fluids is similar to the Bingham plastic and its material model is investigated very well (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1].

The magnetorheological fluids does not follow the properties of Bingham plastic . For example with the decrease of yield stress in magnetorheological fluid it behaves like a visco elastic and it is very complex and it is dependent on the magnetic field density. MR Fluids are known as shear thinning in which viscosity increases yield stress decreases and shear rate also increases. The behaviour of magnetorheological fluids in the off state it behaves like a non newtonion fluid and this non newtonian fluid is temperature independent and deviates like a fluids and after that it is considered as Bingham plastic which is analysised very simply (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1].

Magnetorheological finishing process developed In situ polishing which contains abrasive nano particles which reduce the surface roughness the results we observed increased film thickness ratio by using four ball tester[8].

Magnetorheological finishing process studied magnetorheological abrasive honing to finish external curved surfaces. It used DC electromagnet to measure magnetic flux density. Effect of roughness and workpiece rotation investigated by magnetorheological abrasive honing to improve better finish [9].

1.4 Shear strength of Magnetorheological fluid

In magnetorheological fluid the low shear strength is the primary reason in limit applications. In magnetorheological fluid the absence of external force the maximum shear strength is about 100MPa. When the fluid is compressed in the direction of magnetic field the compressive stress is about 2MPa. Shear strength increases from 1100MPa. In magnetorheological fluid the magnetic particles is replaced by standard magnetic particles for improving shear strength (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1].

1.5 Particle sedimentation of Magnetorheological fluid

The ferro particles in magnetorheological fluid is out of suspension due to density difference between the particles of magnetorheological fluid and carrier fluid. The rate and degree in magnetorheological fluid the primary attributes of construction industry which implementing the magnetorheological devices. Surfactants are used in offset where effect of cost of fluid magnetic saturation increases the max yield stress in the activated state of magnetorheological fluid (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1].

1.6 Common magnetorheological fluid surfactants

The various magnetorheological fluids surfactants are-:

- oleic acid
- tetra methyl ammonium hydroxide
- citric acid
- soy lecithin

The surfactants in magnetorheological fluid decreases the ferroparticle settling in the high rate of unfavourable characteristics of magnetorheological fluids. Idle fluids in magnetorheological fluid does not settle for developing the ideal fluid which is highly impropable for developing the perpetual motion machine to understand the laws of physics. Surfactants settling in magnetorheological fluids is achieved by two ways one is add surfactants and add of spherical ferro magnetic nano particles. The result of addition of nano particles in large particles staying on the suspended layer since the non settling particles interfere the settling of larger microscale particles in the brownian motion. Addition of surfactant in the micelles inn magnetorheological fluids form around the ferromagnetic particles . Surfactants of magnetorheological fluids in the polar head and non polar tail out of one in whitch absorbs the nano particles and the non polar tail from magnetorheological fluids stick out from carrier medium forming the inverse miscelle around the particles and it increases the particle diameter. Surfactants in MR Fluids useful for settling rate prove the determinantal fluid magnetic properties having parameter to maximize the yield stress. Anti settling additives of magnetorheological fluids is a nanosphere based in addition decreases the packing density when ferro particle in the activated state. Decreases fluids on state viscosity in MR Fluids . On state viscosity is the primary concern of MR Fluid applications in magnetorheological fluids , commercial and industrial applications (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1].

1.7 Modes of operation and applications of Magnetorheological fluid

The magnetorheological fluids have three different modes of operation discussed below

Flow mode

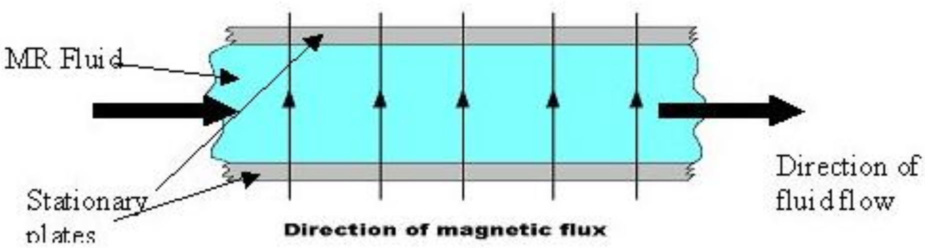

Figure 1.3:Flow mode of magnrtorheological fluid

(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

Shear mode

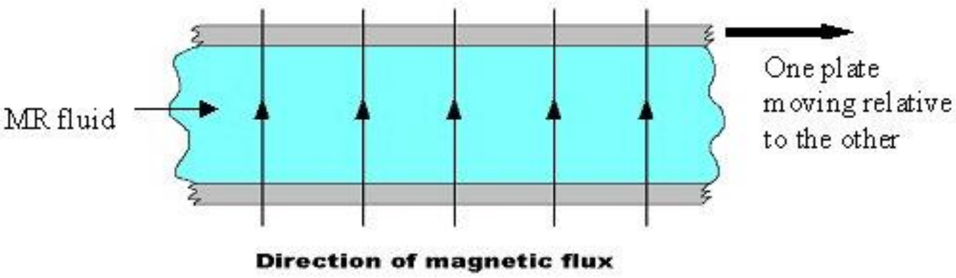

Figure 1.4:Shear mode of magnetorheological fluid

(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

Squeeze flow mode

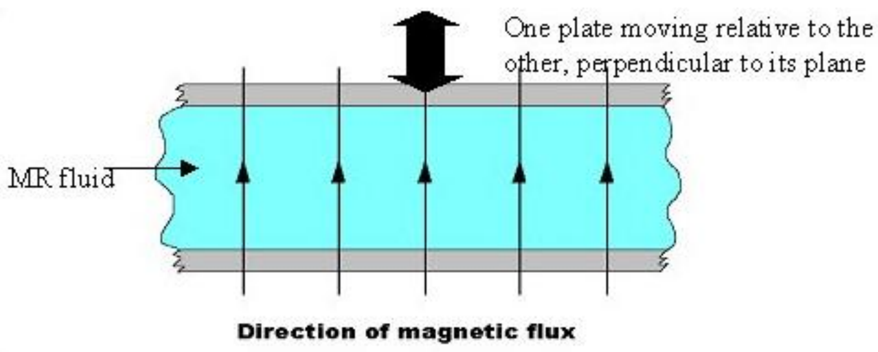

Figure 1.5:Squeeze flow mode of magnetorheological fluid

(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

There are three modes of operations in magnetorheological fluids and these have some applications. In flow mode the dampers and shock absorbers are used as application. There use in flow mode is using movement to controlled the force where magnetic field is applying. In shear mode the clutches and brakes are the applications there use in shear mode is rotational motion must be controlled . In squeeze flow mode it controls the small small movement where large forces are involving(http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

1.8 Limitations of magnetorheological fluid

There are so many limitations in magnetorheological fluids -:

- High density due to the presence of iron in magnetorheological fluids
- High quality fluids which are expensive
- Settling ferro magnetic particles in magnetorheological fluids is a problem in applications.

1.9 Applications of Magnetorheological fluid

The applications of MR Fluids are-:

- Mechanical engineering
- Optics
- Aerospace
- Automotive
- Military and defence

1.10 Magnetorheological finishing

Magnetorheological finishing is also a surface finish technology. In computer controlled MR finishing slurry we polish the optical surfaces. MR Fluid shape stiffness can be controlled and manipulated in a real time. In computer algorithms we will get the final result of surface finish of MR Finishing (http://kn wikipedia.org/wiki/Magnetorheological fluid)[1]

MR finishing process studied analysis of forces to finish flat, curved and freedom surfaces. This study improves to understand the process. Angle of curvature, rotational speed, feed rate, tangential and axial force are the parameters to analysis the forces. We studied in this process was increases the angle of curvature and decreases the reduction in contact area[10].

MR finishing studied the fundamental performance of finishing process in which composed nano-size, microsize and sub microsize particles. It deals with experimental investigation in which magnetic field applying in abrasive particle size, blend ratio and iron powder on polishing characterized. The result we observed magnetic field applying on installing upper magnet. In this process we obtained better surface and large material removal[11].

CHAPTER 2

LITERATURE SURVEY

This chapter provide a literature review of various author in the field of magnetorheological finishing process with or without magnetorheological fluid. This paper provide brief observation from authors work and represented for better understanding.

2.1 Literature review

Maxence *et al*. [2] studied modeling of micro-scale abrasion based on superfinish belt grinding. In this paper there are two design consideration which is very important. These are shift lever force and shiftability arc. In this paper they had chosen a model synchronizing functional force. This model had been chosen according to finish specification which generated virtual input force. It was generated by original fractional function. This method reproduce a surface. This is due to wheel grinding surface. The tool they used here which is soft coated belt. It simulates the abrasive polishing condition. This method applied on initial fractional surface. The basic idea in this paper is higher the height of peak and lower the probability. There were parameters they used in mechanical modeling of micro-scale abrasion based on superfinish belt grinding in which two parameters characterize initial surface and other three parameters which were abrasive polishing process. In this paper they create initial profile by using fractional function.obtain nine values, morphology of initial surface.

Shahrivar *et al*. [3] studied a used ball on three plates geometry which is called be stainless steel-steel point contacts. In that paper they evaluate experimentally properties of the lubricant by using two different colloids in the absence and the presence of the magnetic field. Also evaluate wear damage (optical microscopy, scanning electron microscopy). The results they had lower friction and wear damage during study of the tribological performance of smart fluids and magnetorheological fluids with steel-steel point contacts. In that paper they indicates experimentally effect of particle concentration is better than the particle size.

Uhlmann *et al*. [4] studied a ferro fluids as high positioning systems. The main technical applications in that paper applied magnetic field experimentally and also examine magnetorheological behaviour . High precision positioning with ferrofluids describe different positions of magnetofluidic systems. In that paper also they discussed velocity and accuracy of positioning . They conclude in that paper was high precision, grip and control operation of light objects.

Roy *et al.* [5] reported a design optimization by using different parameters like step by step approach, done manually and time consuming. During design optimization it approached to convert manually optimization to automatic optimization and presents challenges for future optiptimizations. Optimization based on evaluation design and degree of freedom. It presented different approaches and overview of optimization. This paper described that the bigger challenge for optimization technique was scalability. Computer power and algorithm are required for large scale optimization.

Matsumura *et al*. [6] studied a CFD analysis in witch crack free finishing and fluid polishing are presented abrasive water jet process. During machining in machining area abrasives supplied by tapered mask using. On machining area horizontal flow and stagnation under jet are controlled and by mask shape it generates the crack free surface. premachined done by milling applying same method to polishing. During high fluid velocities flow controlled the stagnation under inner wall channels in witch direction flow changes.

Axinte *et al.* [7] studied a High energy fluid jet machining(HEFJ). In HEFJ they generates complex and advanced parts or optimization or machining. In HEFJ during machining difficult to cut materials in different technologies. They use HEFJ for deforming and removing the material from workpiece. The aim in HEFJ machining is presenting different perspective, about machine design, target interactions, quality, modeling, control, supervision,maintenance, health, safety. The conclusion in that paper was to study on various perspectives.

Singh *et al*. [8] studied on material removing. It was developed for 3D workpiece surface and flat surface finish. The tool used in that process was finishing tool in which fluid flow through centre. A polishing spot formed where finishing happened on ball end magnetorheological finishing process. On ferromagnetic workpiece finish surface and material removal presented during machining. In that process a mathematical model developed where normal force induced by magnetic field and it all studied due to complex structure. For unnderstanding wear behaviour and analysed abrasive workpiece of different modes by using scanning electron microscope and atomic force. That process measured normal force. The magnetic normal force variation observed inn that process. The surface roughness change in terms of percentage -11.02% - 2.2%.

Mosleh *et al.* [9] developed insitu nano polishing by using nano lubricants. Utilizing oil based nano lubricants is the method described by insitu nano polishing. Rolling elements contains abrasive nano particles. Bearing elements reduce the surface roughness. The result they found in that process was increased film thickness ratio. Four ball tester used in that process. Normal load, rotational velocity and surface roughness are the three material conditions in that process. Diamond particles contained by engine oil as lubricants. Non contact profilometer used for examined rolling ring track on top. The root mean square roughness decreased by using nano lubricant. The result in that process was lower the frictional torque and increased film thickness ratio.

Sadiq *et al.* [10] studied on magetorheological abrasive honing. In that process external curved surfaces were finished by rotation. In MR Fluid pushed up down this method called MRAH. MRAH described the design and development. DC electromagnet used where magnetic flux density was measured. Aluminium and austenic steel steel particles contained by experimentally where magnetic field understanding. Inn MRAH process they investigated experimentally the effects of surface roughness, rotational workpiece and process duration. They observed in that process improved better finish

Sidpara *et al*. [11] studied forces in freeform surface. In that process finished flat,curved and freedom surface. In that process were got knowledge about forces. During machining improving the process to be understand. Investigating the measure force by experimentally on freedom surface. Angle of curvature, rotational speed, tangential and axial force, feed rate are the three different parameters used to analysis the forces. Normal force is more dominant over other forces. Analysis of forces studied theoretically and experimentally. The result they were got experimentally repeating three times. There were two forces analyzed normal and tangential force in which increased angle of curvature and decreased reduction in contact area.

Furuya *et al.* [12] studied on performance on magnetic compound fluid in contact free finishing on surface. In that process composed nano-size, micro-size and sub micro-size particles. It deals with applying magnetic field, abrasive particles size, iron powder, blend ratio these all investigated by experimentally. The results were obtained after magnetic field applying on the upper magnet. During machining we conclude better work surface and large material removal. That process for polishing large sized particles were used. By experiment they got optimum values 20 and 20-40 wt %.

Garitaonandia *et al*. [13] reported on a piezoelectric actuators which presents noval methodology to optimize vibration control. This works on centerless grinding machine. From that process they obtained compact and control systems which are efficient which was applied on machine characteristics. They simulated the new active control system in order to reduce space model to verify the effectiveness on previous solution. From the new design a new active control system manufactured the results were obtained by experiment from different conditions were shown. The redesign of active system in vibration control make it possible by theoretically and experimentally results.

Wang *et al.* [14] studied permanent magnetic yoke for MR polishing. This process developed a magnetic excitation unit. It improves the efficiency. For simulation finite element modeling used. Trough speed, work excitation crack width and particle concentration are the four factors effect on MR polishing by using permanent mgnetic coke. The final test performed used glass as a specimen to examine the performance of polishing. From this process observed that polishing area is larger than conventional MR polishing.

Kumar *et al.* [15] studied nanofinishing of freedom surface. The important part in that process was freeform complex surface. In that process we required nanolevel surface roughness value. For optimization this process was very difficult. This process applied on internal surface finishing so far. The geometry for that process was simple. That process improves topography. The principle idea for that process was large hydrodynamic pressure coupled. A smooth mirror like finished surface achieved from that process. The finishing rate were improved from that process. Two motions were controlled from that process. Finishing surface roughness value reduced, increased uniformity and enhance finishing rate in that process. The ranging of surface roughness is 35 to 78nm.

Cheng *et al.* [16] developed to design six axis high precision machine tool. For designing six axis machine tool sub aperture lapping technique were used. It worked on a computer controlled optical surface system. Grinding, polishing and profile measuring are the combination used for designing six axis high precision machine tool. There were multiple degree of freedom used for designing. Noval dual touch trigger were designed to measure the accuracy of shape. This was tested by aspherical surface. This was done on model METRO-MT60. Next model they designed was METRO-M12. This was designed calibrating device. This was done on new CNC machining system. There were two coordinates applied. Material removal function were analyzed in that process. The accuracy were 1um PV. The resolving power were 0.2-0.5um. The initial was 7.648um and the final were 0.728um. These results were obtained during designing six axis high precision machine tool.

Park *et al.* [17] studied active materials for machining process. The applications of active materials were used for manufacturing machining processes. The concept of import and background were briefly discussed in that process. Relative themes were applied by using active materials. This was done all by studying theoretically and experimentally. Future research areas were discussed for allowing actuation, sensing and fully integrated operations. For conclusion it improves the performance.

Jung *et al.* [18] studied finishing on hard materials by using iron cintered compounds. The use of that process for ultra fine surfaces on micrometer structures. The Al_2O_3-TiC hard disk slider are not applicable on hard materials. Conventional rotational tool were used due to low efficiency and rotational speed. Material removal rate is responsible by main mechanism. Wheel type MR finishing used for hard materials. The solution were done by two approaches. The first approach were rectilinear alternating motion for improving conditions. The second approach were magnetizable abrasives which increased lifetime of consumables and material removal rate.

Singh *et al.* [19] developed nanofinishing for 3D surfaces. This process used to finish ferromagnetic and non magnetic materials. A special MR fluid used for nanofinishing of 3D surfaces. Previous methods and devices were incapable for that process. There were no limitation on relative moment for nanofinishing. The nanofinishing were used for 2D and 3D surface. The applications of nanofinishing for 3D surfaces were aerospace, automotive and manufacturing industry. Computer controlled designed and manufacturers setups were designed for nanofinishing. In nanofinishing characteristics and performance were study. In nanofinishing the results obtained was to described effect on finishing time.

Singh *et al.* [20] studied nanofinishing 3D ferromagnetic workpiece. In that process ball end MR fluid generated at the tip. The tool were used in that process was rotating. That tool used for finishing spot. Surface finish and performance evaluation were focussed on nanofinishing 3D ferromagnetic workpiece. There were three dimensional ferromagnets used for nanofinishing. That process were made by milling process for different angles 30º,45º,curved surface. To study the effect on final surface roughness by experiments. The experiment were performed on flat ground surface to study process parameter. Magnetic flux density distribution were studied by finite element analysis. The surface roughness reduced as 19.7um for 120mn the result were obtained that tis process is effective for finishing.

Mathai *et al.* [21] studied on material removing during abrasives.the process were used for deburring of machine parts for understanding material removing is lacking. Brush deburring rate, surface roughness, change in foil thickness as spindle speed, brush nominal penetration were investigated in that process for material removing during abrasives. Ploughing and chip formation were analyzed during material removing. The final velocity 7m/s dominates over initial velocity 2m/s for material removing. Remove long slender burrs this was done by fatique fracture under cyclic loading. During material removing reduced surface roughness and increased the further brushing. During material removing change in foil thickness is less than equal to 1um.

Jiao *et al*. [22] reported the performance of magnetic compound fluid on ultra fine finish for optical glass. A thin MCF slurry generates on MCF wheel. This was generated on circumferential surface. Ring shaped permanent magnet like shape were placed between two non magnetic plates. The particles composed like nano size, micron size and sub micron sized. This fundamental performance described modification of that process. For measuring the performance esperiment would setup. Effect of wheel rotational speed, clearance, removing workpiece material, roughness were investegated in MCF wheel. Polishing surface is measured in MCF wheel. Structure of MCF slurry were examined in MCF wheel. Magnetic field distribution were analysed during fundamental performace on MCF wheel. The results were obtained on MCF wheel was more material removing, better surface obtained, better worfk surface, higher wheel rotational speed.

Sooraj *et al.* [23] studied on fine finish of internal surface on elastic abrasives. It generates ultra fine finish on internal surfaces. The specimen for fine finishing on internal surface was tabular. The process which had capability to deform in confirmity to work surface called elastomer balls. Mathematical model were used to analysed a material removal mechanism methodology. Response surface methodology were used for doing validation by systematic experimentation procedure. The central composite designed for experimental study. The results were obtained during fine finish of internal surface were effect of axial pressure, abrasive grain size, simple and cost effective.

Ahmed *et al.* [24] studied on control vibration during machining on MR damper by FEA based modeling. That process were used to determine vibration and deflection. It occurs on end milling process. The geometry was complex. Modeling and structural behaviour were the important role for control vibrations. A simple beam were considered. The application for that process were FEM. It was performed by static analysis. Effect of dynamic response with or without damper studied by FEA based modeling. Cutting forces interactions done by metal cutting operations. Damper input current utilized by FEA modeling for cotrol vibration. Bingham number identifies increased stiffness, magnetic field, produce damper effect. The results in that processes were obtained a quality, deflection reduction and vibration marks. By ANSYS damper input current were 0 to 2 ampeere. The cutter material were HS steel and carbide for controlling vibration by FEA modeling.

Niranjan *et al.* [25] studied flow behaviour of MR fluid and finishing. MR fluid composed of small size content of CIPs. Physica MCR-301 rheometer used for flow behaviour. Steady state rheograms used evaluation of flow behaviour.during experiment 16% CIPs CS grade, 4% CIPs HS grade, 25% abrasives, 55% base fluid werefound for yield shear stress and viscosities. The results were found during experimentsshowed yield shear stress and viscosity improves as compared to other fluids. Scanning electron microscope were used to study prepared samples.

Guo *et al*. [26] developed the effect of pressure and shear stress on material removal rate. MCF polishing used to polish optical glass under rotary magnetic field. Different variety materials and soft optical polymers to hard optical polymers polished by MCF slurry successfully. This study measured normal and shear stress. It generates on polishing zone done by polishing. Spot polishing of boro silicate glass used for finding material removal. Magnet revolution speed, MCF rotational speed and working gap also find. The results were obtained that P is higher and maximum shear stress about 5mm. MRR is more dominated by pressure than by shear stress.

2.2 Research gap/Motivation of the present work

Many authors had done research on material removal, magnetorheological abrasive honing, magnetorheological abrasive flow, nano-finishing process for 3D surfaces, forces, modeling and simulation of surface roughness in ball end magnetorheological finishing tool. But none of the authors have been investigated thermal analysis in ball end magneto rheological finishing tool. In ball end magnetorheological finishing tool need to be calculated temperatures at different magnetizing currents. A magnetorheological fluid is a type of smart fluid when it is subjected to magnetic field it increases its viscosity when the temperature increases its viscosity decreases. Key parameter has been taken from the literature survey to calculate temperatures in ball end magnetorheological finishing tool. Those key parameters are listed below.

- Magnetizing current
- Working gap
- Nozzle speed
- Temperature
- Heat

2.3 Research objectives

- To do the thermal analysis of ball end magnetorheological finishing tool.
- To calculate the temperature of magnetorheological ball tool tip surface at the various magnetizing currents.
- To investigate the requirement of cooling coil for the tool when temperature at the tool tip surface start increasing above 50ºC.
- To determine the coolant coil controlled temperature when cooling coil required for higher range of magnetizing currents.
- To validate the calculated tool tip surface temperature with experiments.

2.4 Methodology

- The thermal analysis of ball end magnetorheological finishing tool has been done at different magnetizing currents.
- The temperature of the tool tip surface has been calculated at different magnetizing currents applied on the electromagnet coil using Fourier law of equation.
- The required coolant coil incorporated to control and monitor the finishing tool tip surface temperature less than to 50ºC.
- The coolant coil temperature controlled and maintained as per the applied magnetizing currents which causes to increase the tool tip surface temperature above 50ºC.

CHAPTER 3

MATHEMATICAL MODEL FOR FINDING THE TOOL TIP SURFACE TEMPERATURE

3.1 Introduction

Objective of the experiments was to investigate the " **Thermal analysis of ball end magnetorheological finishing tool** ". Experimental setup has been fabricated and carried out at the magnetizing currents 1A to 4A. Since in the present experimental setup cooling coil so far has not been incorporated, therefore experiments were performed at magnetizing currents 1A to 4A because without cooling coil the temperature of electromagnet coil increases abruptly. Experimental setup consists of finishing tool(electromagnet coil, central rotating core and cooling coil to be incorporated), RTD(Resistance temperature detectors)thermocouple, regulated DC power supply as shown in Fig 3.1.

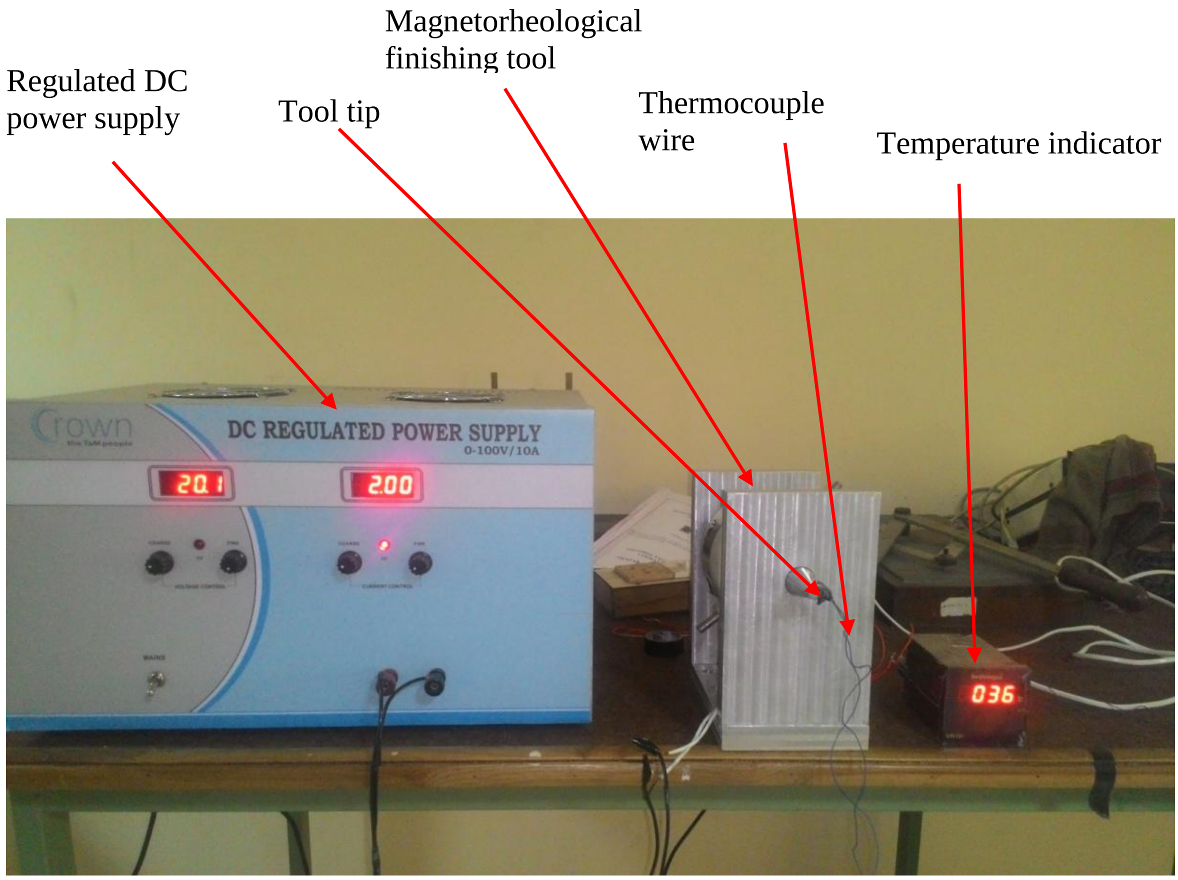

Figure 3.1: Experimental setup to measure the temperature at the tool tip surface of ball end magnetorheological finishing tool

The experimental setup to measure the tool tip surface temperature is shown in fig 3.1. The Experimental setup consists of finishing tool(electromagnet coil, central rotating core and cooling coil to be incorporated), RTD(Resistance temperature detectors)thermocouple, regulated DC power supply. The regulated DC power supply used to apply magnetizing currents to ball end magnetorheological finishing tool. The magnetizing currents has been applied to the magnetorheological finishing tool in which electromagnet coil, central rotating tool core is attached. The thermocouple wire is attached to the tool tip surface to measure the temperature. The temperature has been measured by resistance temperature detectors(RTD)thermocouple at magnetizing currents from 1A to 4A. Photograph of magnetorheological finishing tool is shown in fig 3.2. This symmetric of magnetic flux flow lines in finishing tool when magnetizing currents is applied as shown in fig 3.3.

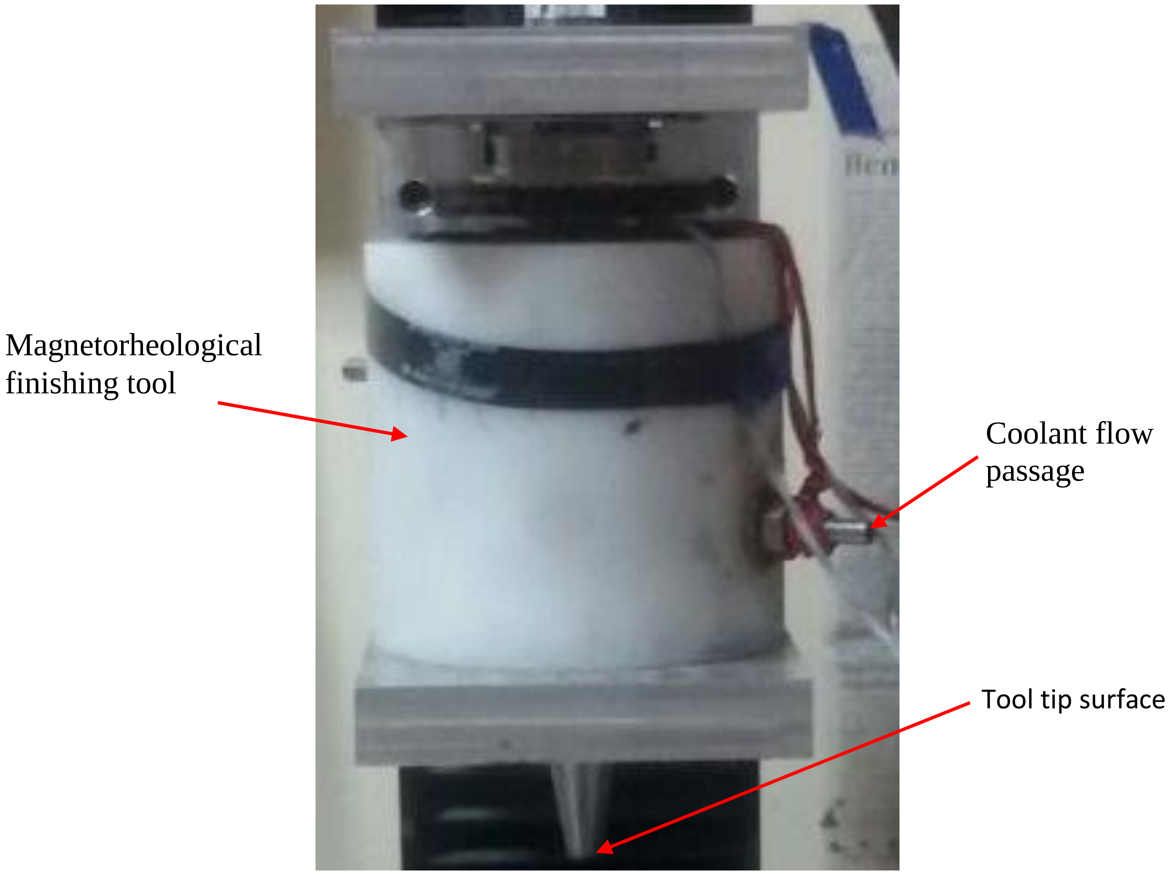

Figure 3.2 Photograph of ball end magnetorheological finishing tool to measure the tool tip surface temperature.

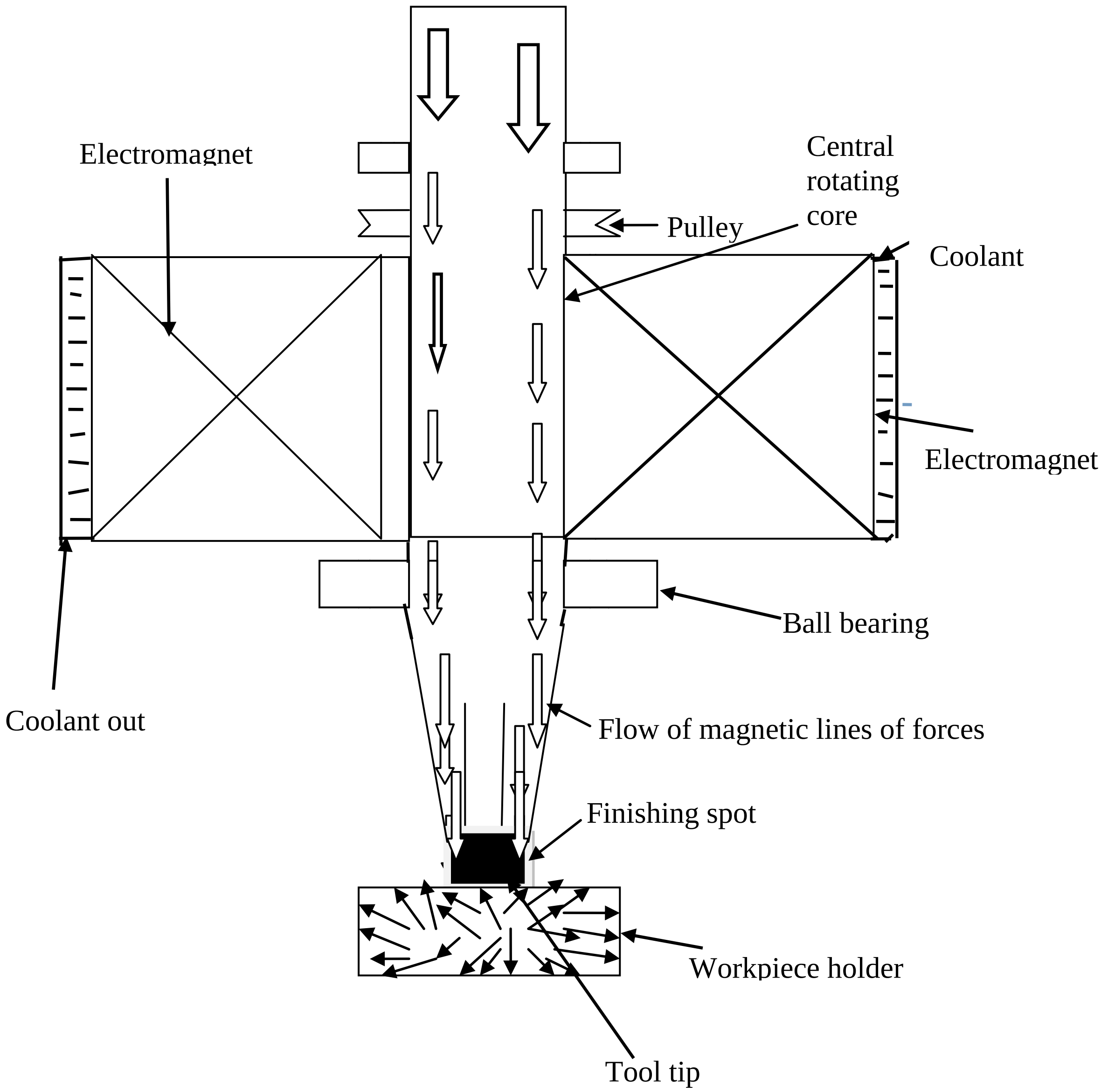

Figure 3.3: Setup of ball end magnetorheological finishing tool

3.2 Calculations of temperatures of tool tip surface

3.2.1 Calculations of total heat at the Electromagnet coil

$$Q = I^2 R_T \qquad (3.1)$$

where, Q = total heat(W)

I = current(A)

R_t =thermal resistance per sec(Ω/sec)

Given, $R_t = 8\Omega$

At 1 amp, $Q = (1)^2 \times 8 = 8W$

At 2 amp, $Q = (2)^2 \times 8 = 32W$

At 3 amp, $Q = (3)^2 \times 8 = 72W$

At 4 amp, $Q = (4)^2 \times 8 = 128W$

At 5 amp, $Q = (5)^2 \times 8 = 200W$

At 6 amp, $Q = (6)^2 \times 8 = 288W$

At 7 amp, $Q = (7)^2 \times 8 = 392W$

Table 3.1: Calculations of total heat at various magnetizing currents on the electromagnet coil

Magnetizing currents (A)	Total heat(W)
1A	8W
2A	32W
3A	72W
4A	128W
5A	200W
6A	288W
7A	392W

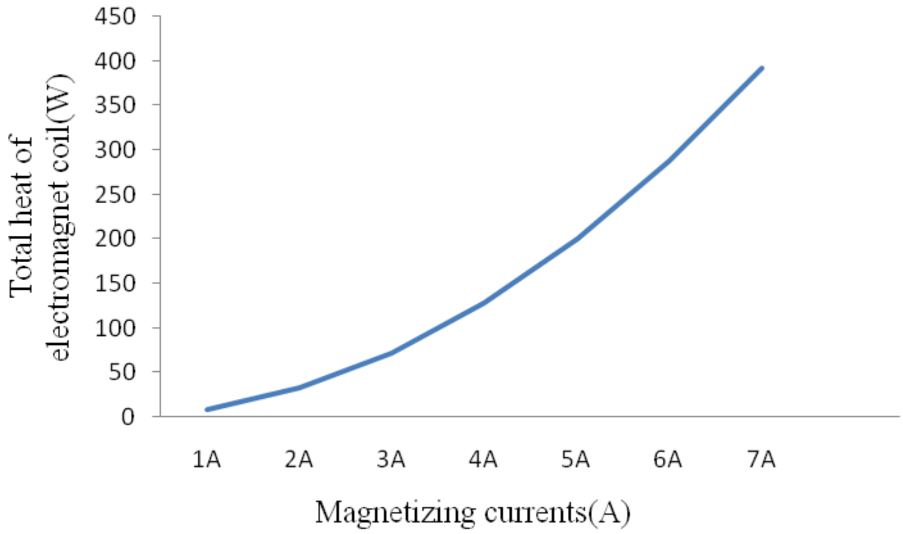

Figure 3.4: Graph of magnetizing currents(A) vs total heat on the electromagnet coil(W)

From calculations, it has been seen that when magnetizing currents increases, the total heat on the electromagnet coil also increases as shown in fig 3.4 and table 3.1

3.2.2 Calculations of Temperature of electromagnet coil surface

From fourier law of heat transfer equation,

$$Q = K \times A \times {}^{dt}\!/_{dx} \tag{3.2}$$

where, K = thermal conductivity of copper (k=400)(W/m^2 K)

A = area of coil(mm^2)

dt/dx = temperature difference(ºC/mm)

Diameter, d = 40mm

At 1amp,

$$Q_{\substack{TOTAL\\HEAT}} = K \times A \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - T_{AMBIENT\,AIR} \right) / dx$$

Assumed ambient temperature for calculating the electromagnet coil surface temperature is 45ºC.

$$8 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - 45 \right) / 0.04$$

$$8 = 401.92\ T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - 18089.4/0.04$$

$$0.32 + 18089.4/401.92 = T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$$

$$T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 45.007°C$$

By using the same equation 3.2 to calculate temperatures on the electromagnetic coil surface at different magnetizing currents.

At 2 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 45.03°C$

At 3 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 45.07°C$

At 4 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$ = 45.12°C

At 5 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$ = 45.19°C

At 6 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$ = 45.28°C

At 7 amp, $T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$ = 45.39°C

Table 3.2: Calculations of temperature on the electromagnet coil surface at various magnetizing currents.

Magnetizing currents	Temperature of electromagnet coil surface
1A	45.007ºC
2A	45.03ºC
3A	45.07ºC
4A	45.12ºC
5A	45.19ºC
6A	45.28ºC
7A	45.39ºC

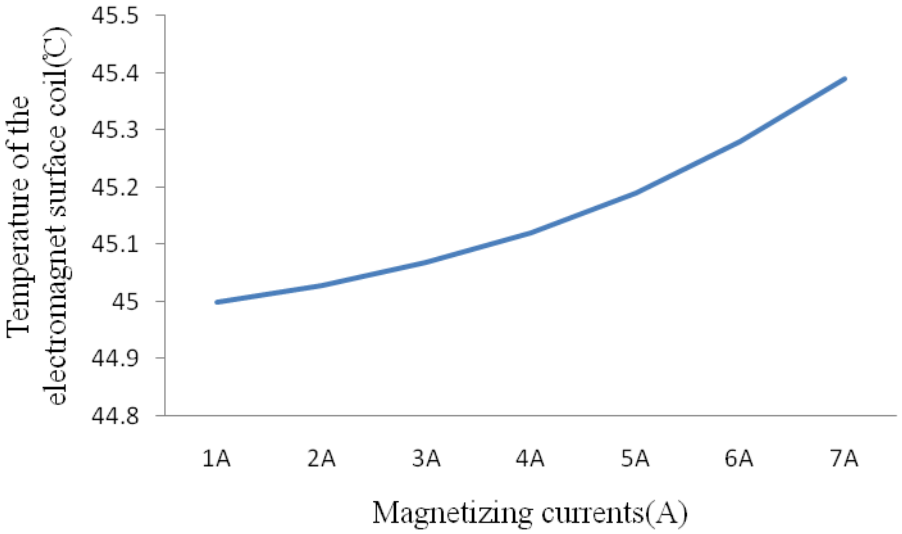

Figure 3.5:Graph of temperature of electromagnet coil surface(°C) vs magnetizing currents(A).

From calculations, it has been seen that when magnetizing currents increases, the temperature on the electromagnet coil surface also increases as shown in fig 3.5 and table 3.2

3.2.3 Calculations of heat transfer on electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = ?$$

By using the same formula,

$$Q = K \times A \times {}^{dt}\!/_{dx} \tag{3.3}$$

At 1 amp**,**

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = K \times A \times \left(T_{\substack{ELECTRMAGNET\\COIL\\SURFACE}} - T_{\substack{AMBIENT\\AIR}} \right) / dx$$

$$= 400 \times 2 \times 3.14 \times (.2) \times (.8) \times (45.00 - 45)/0.04$$

$$= 401.92 \times 0.007/0.04$$

$$= 7.05\text{W}$$

Similarly, to calculate heat transfer on the electromagnet coil surface at different magnetizing currents by using the same equation 3.3.

At 2 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 30.14W

At 3 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 70.33W

At 4 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 120.57W

At 5 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 190.91 W

At 6 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 281.344 W

At 7 amp, , $Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = 391.8 W

Table 3.3: Calculations of heat transfer on the electromagnet surface coil at various magnetizing currents.

Magnetizing currents(A)	Heat transfer of electromagnet coil surface (W)
1A	7.05W
2A	30.14W
3A	70.33W
4A	120.57W
5A	190.91W
6A	281.344W
7A	391.8W

The calculations of heat transfer of electromagnet coil surface at various magnetizing currents has been calculated to calculate the tool tip temperature surface. It was observed that when the magnetizing currents increases the heat transfer on the electromagnet coil surface also increases as shown in table 3.3.

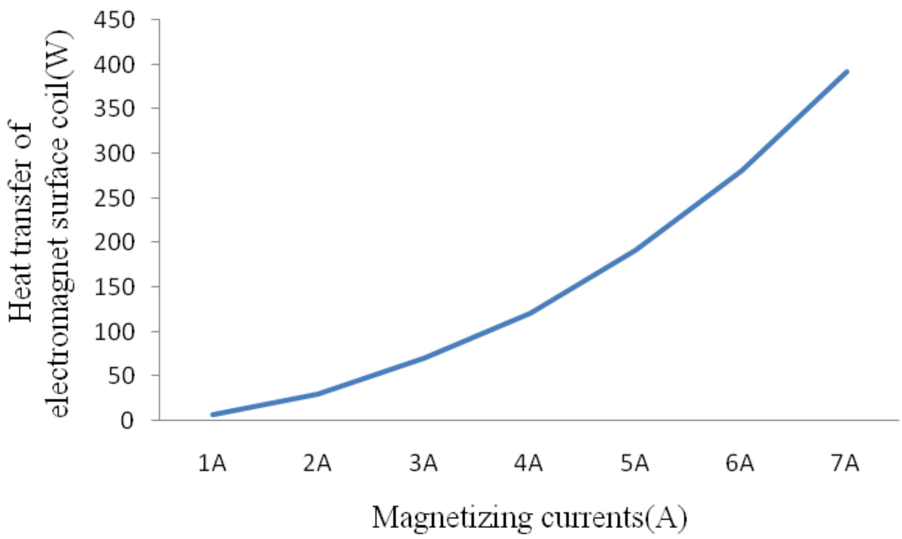

Figure3.6: Graph of heat transfer of electromagnet surface coil(W) vs magnetizing currents(A)

Fig 3.6 shows that at various magnetizing currents the heat transfer on the electromagnet coil surface has been calculated. It was observed that the heat transfer on the electromagnet coil surface increases when the magnetizing current increases from 1A to 7A on the electromagnet coil surface.

3.2.4 Calculations of heat transfer of ambient air

Total Heat = Heat conducted + Heat convective (3.4)

At 1 amp,

Total Heat = Heat conducted + Heat convective

$$8 = 7.05 + Q_{\substack{AMBIENT \\ AIR}}$$

$$Q_{\substack{AMBIENT \\ AIR}} = 0.95 \text{ W}$$

Similarly, by using the same equation 3.4 to calculate heat transfer of ambient air at different magnetizing currents-:

At 2 amp, $Q_{\substack{AMBIENT \\ AIR}} = 1.86$ W

At 3 amp, $Q_{AMBIENT\ AIR} = 1.67\ W$

At 4 amp, $Q_{AMBIENT\ AIR} = 7.43\ W$

At 5 amp, $Q_{AMBIENT\ AIR} = 9.09\ W$

At 6 amp, $Q_{AMBIENT\ AIR} = 6.7\ W$

At 7 amp, $Q_{AMBIENT\ AIR} = 0.2\ W$

Table 3.4: Calculations of heat transfer of ambient air at different magnetizing currents

Magnetizing currents(A)	Heat transfer of ambient air(W)
1A	0.95W
2A	1.86W
3A	1.67W
4A	7.43W
5A	9.09W
6A	6.7W
7A	0.2W

The calculations of heat transfer of ambient air at various magnetizing currents has been calculated to calculate the tool tip surface temperature. It was observed that the heat transfer of ambient air increases when the magnetizing currents increases from 1A to 7A as shown in table 3.4.

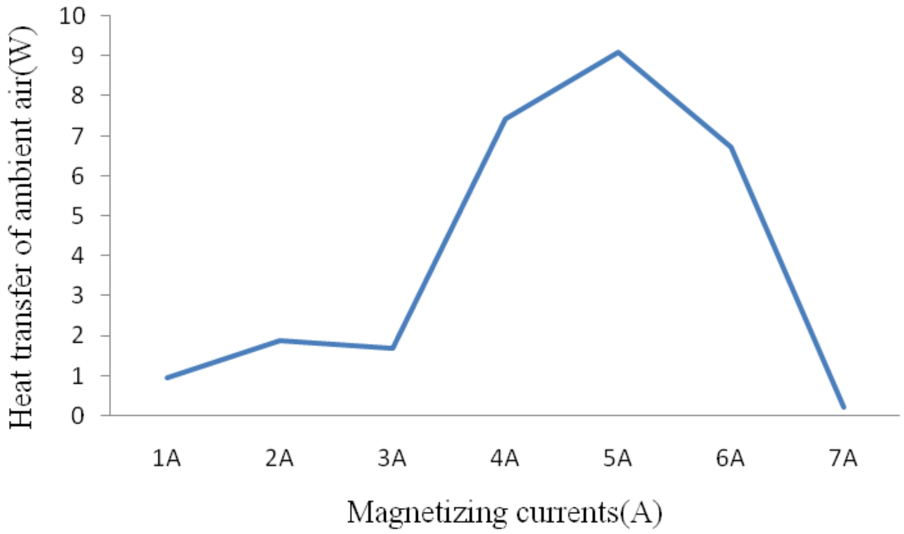

Figure 3.7: Graph of heat transfer of ambient air(W) vs magnetizing currents(A)

Fig 3.7 shows that at various magnetizing currents the heat transfer of ambient air has been calculated. It was observed that the heat transfer of ambient air increases from 1A to 2A then decreases at 3A and it increases again from 3A to 5A then decreases from 5A to 7A.

3.2.5 Calculations of temperature of ambient air

$$Q = h \times A \times {}^{dt}\!/_{dx} \qquad (3.5)$$

where,

Q = heat transfer(W)

h = convective heat transfer coefficient of air (1000)(W/m^2 K)

$T_{\substack{AMBIENT \\ AIR}}$ = temperature of ambient air(°C)

$T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}}$ = temperature of electromagnet surface coil(°C)

At 1 amp ,

$$Q = h \times A \times \left(T_{\substack{AMBIENT \\ AIR}} - T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} \right) / dx$$

$0.95 = 1000 \times 8 \times 3.14 \times (.2) \times (.8) \times (T_{\substack{AMBIENT \\ AIR}}$ - 45.00)/0.04

$0.95 = 4019.2\ (T_{\substack{AMBIENT \\ AIR}}$ -45.00)

$0.95 = 4019.2\, T_{\substack{AMBIENT \\ AIR}} - 18089.5$

$4019.2\, T_{\substack{AMBIENT \\ AIR}} = 18089.5$

$T_{\substack{AMBIENT \\ AIR}} = 45.007°C$

Similarly, to calculate temperature of ambient air at various magnetizing currents by using same equation 3.5 .

At 2 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.03°C$

At 3 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.07°C$

At 4 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.12°C$

At 5 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.19°C$

At 6 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.28°C$

At 7 amp, $T_{\substack{AMBIENT \\ AIR}} = 45.39°C$

Table 3.5 Calculations of temperature of ambient air at various magnetizing currents

Magnetizing currents(A)	Temperature of the ambient air($°C$)
1A	45.007ºC
2A	45.03ºC
3A	45.07ºC
4A	45.12ºC
5A	45.19ºC
6A	45.28ºC
7A	45.39ºC

The calculations of temperature of ambient air at various magnetizing currents has ben calculated to calculate tool tip surface temperature. It was observed that the temperature of the ambient air increases when the magnetizing currents increases from 1A to 7A as shown in table 3.5.

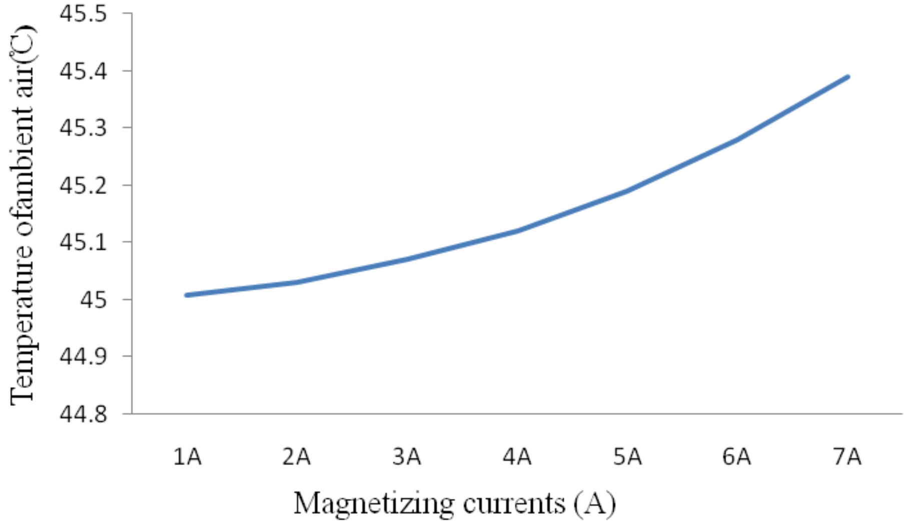

Figure 3.8: Graph of temperature of ambient air(ºC) vs magnetizing Currents(A)

Fig 3.8 shows that at various magnetizing currents the temperature of the ambient air has been calculated. It was observed that the temperature of the ambient air increases when the magnetizing current increases from 1A to 7A.

3.2.6 Calculations of temperature of central rotating tool core surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.6)$$

where,

K = thermal conductivity of iron (k=79.5)(W/m^2 K)

A = area of coil(mm^2)

dt/dx = temperature difference($°C/mm$)

Diameter, d = 40 mm

At 1 amp**,**

$$Q = K \times A \times \left(T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} - T_{\substack{AMBIENT\\AIR}} \right) / dx$$

7.05 = 79.5$\times$2$\times$3.14$\times$(.2)$\times$(.8)$\times$($T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}}$ - 45.00)/0.04

7.05 = 79.8816$\times$($T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}}$ - 45.007)/0.04

2.82 = 79.8816 $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}}$ - 3595.23)

$T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}}$ = 45.04°C

Similarly, to calculate temperatures of central rotating tool core surface at various magnetizing currents.

At 2 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 45.18°C$

At 3 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 45.42°C$

At 4 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 45.72°C$

At 5 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 46.14°C$

At 6 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 46.68°C$

At 7 amp , $T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 47.35°C$

Table 3.6: Calculations of temperatures of central rotating tool core surface at various magnetizing currents.

Magnetizing currents (A)	Temperatures of the central rotating tool core surface($°C$)
1A	45.04ºC
2A	45.18ºC
3A	45.42ºC
4A	45.72ºC
5A	46.14ºC
6A	46.68ºC
7A	47.35ºC

The calculations of temperatures of central rotating tool core surface at various magnetizing currents has been calculated to calculate the tool tip surface temperature. It was observed that the temperatures of the central rotating tool core surface increases when the magnetizing currents increases from 1A to 7A as shown in table 3.6.

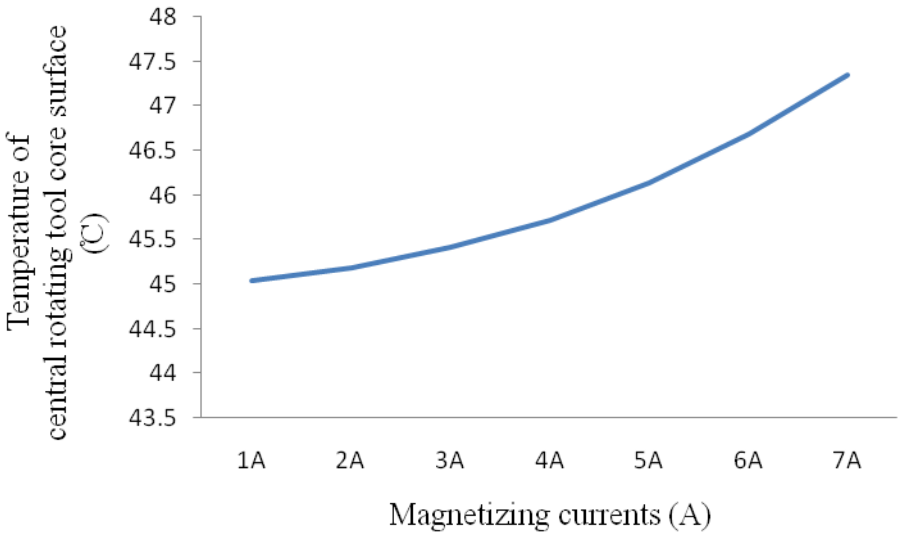

Figure 3.9: Graph of temperatures of central rotating tool core surface(ºC) vs magnetizing currents(A)

Fig 3.9 shows that at various magnetizing currents the temperature of the central rotating tool core surface has been calculated. It was observed that the temperatures of the central rotating tool core surface increases when the magnetizing current increases from 1A to 7A.

3.2.7 Calculations of heat transfer of central rotating tool core surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.7)$$

At 1 amp ,

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (45.04 - 45.007)/0.04$$

$$= 79.8816\ (45.04 - 45.007)/0.4$$

$$= 6.59\ W$$

Similarly,

At 2 amp , $Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 29.95\ W$

At 3 amp , $Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 69.89\ W$

At 4 amp , $Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 119.8\ W$

At 5 amp , $Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 189.71W$

At 6 amp , $Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 279.5\ W$

At 7 amp , $Q_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}}$ = 391.4 W

Table 3.7: Calculations of heat transfer of central rotating tool core surface at various magnetizing currents

Magnetizing currents(A)	Heat transfer of central rotating tool core surface (W)
1A	6.59W
2A	29.95W
3A	69.89W
4A	119.8W
5A	189.71W
6A	279.5W
7A	391.4W

The calculations of heat transfer of central rotating tool core surface at various magnetizing currents to calculate the temperatures of tool tip surface. It was observed that the heat transfer of central rotating tool core surface increases when the magnetizing current increases from 1A to 7A as shown in table 3.7.

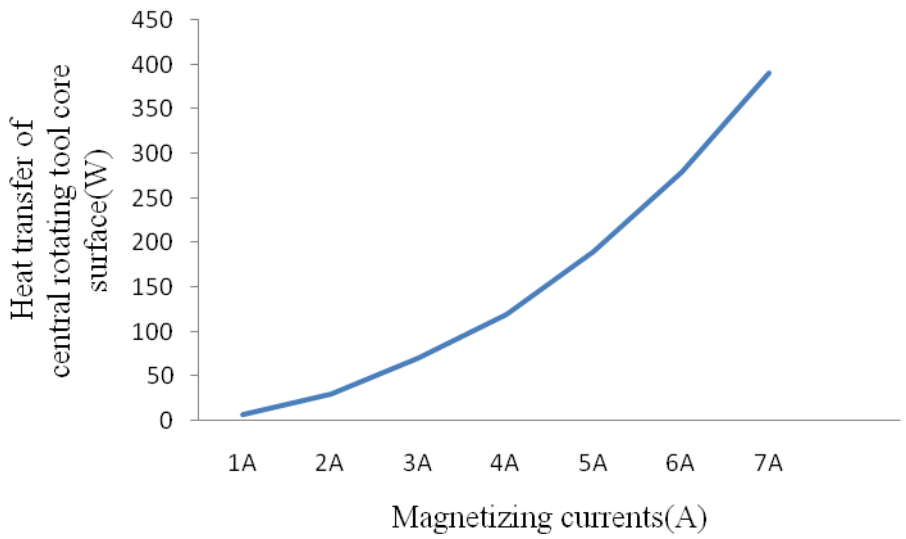

Figure 3.10: Graph of heat transfer of central rotating tool core surface vs magnetizing currents

Fig 3.10 shows that at various magnetizing currents the heat transfer of the central rotating tool core surface has been calculated. It was observed that the heat transfer of the central rotating tool core surface increases when the magnetizing current increases from 1A to 7A.

3.2.8 Calculations of temperatures at the tool tip surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.8)$$

where,

A = area of tip

= $1/2 \times b \times h$

= $1/2 \times .07 \times .2$

= $.007mm^2$

At 1 amp ,

$$Q = K \times A \times \left(T_{\substack{TOOL\\TIP\\SURFACE}} - T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} \right) / dx$$

$6.59 = 79.5 \times .007 \times (T_{TOOL\ TIP\ SURFACE} - 45.04)/.07$

$.4613 = (0.556\, T_{TOOL\ TIP\ SURFACE} - 25.04)$

$T_{TOOL\ TIP\ SURFACE} = 25.50/0.556$

$T_{TOOL\ TIP\ SURFACE} = 45.86°C$

Similarly,

At 2 amp , $T_{TOOL\ TIP\ SURFACE} = 48.94°C$

At 3 amp , $T_{TOOL\ TIP\ SURFACE} = 54.21°C$

At 4 amp , $T_{TOOL\ TIP\ SURFACE} = 60.78°C$

At 5 amp , $T_{TOOL\ TIP\ SURFACE} = 70.00°C$

At 6 amp , $T_{TOOL\ TIP\ SURFACE} = 81.83°C$

At 7 amp , $T_{TOOL\ TIP\ SURFACE} = 96.58°C$

Table 3.8: Calculations of temperatures of the tool tip surface at various magnetizing currents.

Magnetizing currents(A)	Temperatures of tool tip surface($°C$)
1A	45.86ºC

2A	48.94ºC
3A	**54.21**ºC
4A	60.78ºC
5A	70.00ºC
6A	81.83ºC
7A	96.58ºC

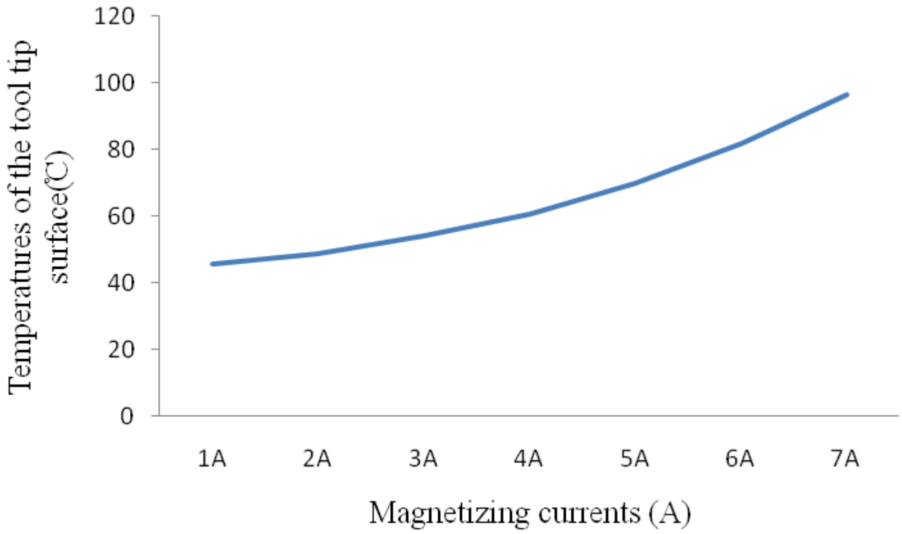

Figure 3.11: Graph of temperatures of the tool tip surface(ºC) vs magnetizing currents(A)

The calculations of temperatures of the tool tip surface at various magnetizing currents has been calculated to calculate the tool tip surface temperature. It was observed that the temperature at the tool tip surface start increases above 50ºC when the magnetizing current increased from 3A to 7A. This affects the finishing process due to temperature increases which decreases the viscosity MR finishing fluid at the tip surface of the tool. The finishing process in thermal analysis of ball end magnetorheological finishing tool from 1A to 2A magnetizing current is safe because the temperature at the tool tip surface is less than 50ºC as shown in table 3.8 and fig 3.11.

3.2.9 Calculations heat transfer at the tool tip surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.9\ )$$

At 1 amp ,

$Q_{TOOL\ TIP\ SURFACE}$ = $79.5 \times .007 \times (45.86\text{-}45.04)/.07$

= $0.556 \times (45.86 - 45.04)/.07$

= 6.59 W

Similarly ,

At 2 amp , $Q_{TOOL\ TIP\ SURFACE}$ = 29.89 W

At 3 amp , $Q_{TOOL\ TIP\ SURFACE}$ = 69.88W

At 4 amp , $Q_{TOOL\ TIP\ SURFACE}$ = 119.72 W

At 5 amp , $Q_{TOOL\ TIP\ SURFACE}$ =189.68 W

At 6 amp , $Q_{TOOL\ TIP\ SURFACE}$ = 279.44 W

At 7 amp , $Q_{TOOL\ TIP\ SURFACE}$ = 391.37 W

Table 3.9: Calculations of heat transfer at the tool tip surface at various magnetizing currents

Magnetizing currents(A)	Heat transfer of tool tip surface(W)
1A	5.96W

2A	29.89W
3A	70.27W
4A	126.16W
5A	198.43W
6A	287.15W
7A	391.77W

The calculated heat transfer at the tool tip surface temperature at various magnetizing currents are reported in table 3.9. It was observed that heat transfer of the tool tip surface temperature increases when the magnetizing current increases from 1A to 7A as shown in table 3.9.

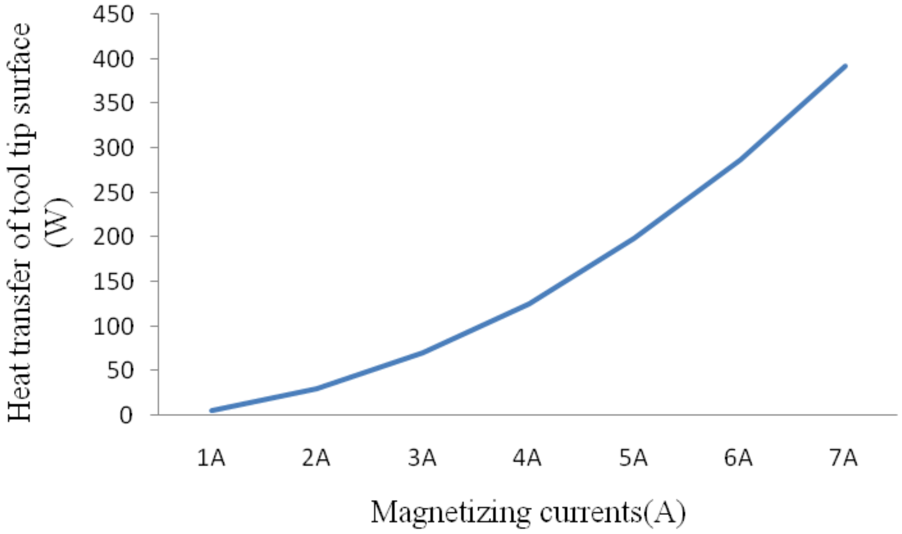

Figure 3.12: Graph of heat transfer of tool tip surface(W) vs magnetizing currents

Fig 3.12 shows that at various magnetizing currents the heat transfer at the tool tip surface has been calculated. It observed that the heat transfer at the tool tip surface increases when the magnetizing current increases from 1A to 7A.

3.3 Calculate temperatures at tool tip surface by passing coolant at 3A

Equation of temperature of electromagnet coil surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.10)$$

$$Q = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{COOLANT} \right) / \, dx$$

$$72 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - 35 \right) / \, 0.5$$

$$T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 35.07^{o}\text{C}$$

Equation of heat transfer at electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.11)$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{COOLANT} \right) / \, dx$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times (35.07 - 35) / \, 0.5$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 70.33\text{W}$$

Equation of temperatures of central rotating tool core surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.12)$$

$$70.33 = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} - 35.07)/.4$$

$$T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 35.42^{o}C$$

Equation of heat transfer of central rotating tool core surface

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.13)$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (35.42 - 35.07)/.4$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 83.87W$$

Equation of temperature at the tool tip surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.14)$$

$$83.87 = 79.5 \times .007 \times (T_{\substack{TOOL\\TIP\\SURFACE}} - 35.42)/.07$$

$$T_{\substack{TOOL\\TIP\\SURFACE}} = 45.96^{o}C$$

Equation of heat transfer at the tool tip surface

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = K \times A \times dt/dx \quad (3.15)$$

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = 79.5 \times .007 \times (45.96 - 35.42)/.07$$

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = 83.79\text{W}$$

Table 3.8 shows that at 3A magnetizing current the temperature at the tip goes above 50ºC. Due to high temperature and less viscosity it effects the finishing process, therefore the coolant coil required at 3A magnetizing current to the electromagnet. From these above calculations it has been investigated that if the coolant temperature controlled by less than or equal to 35ºC then the temperature at the tool tip surface goes below 50ºC.

3.4 Calculate temperatures at tool tip surface by passing coolant at 4A

Equation of temperature of electromagnet coil surface

$$Q = K \times A \times dt/dx \quad (3.16)$$

$$Q = K \times A \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - T_{COOLANT} \right) / dx$$

$$128 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - 30 \right) / 0.5$$

$$T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 30.12^{\circ}\text{C}$$

Equation of heat transfer of electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = K \times A \times dt/dx \quad (3.17)$$

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = K \times A \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - T_{COOLANT} \right) / dx$$

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 400\times 2\times 3.14\times (.2)\times(.8)\times(30.12-30)/0.5$$

$$Q_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} = 120.57\text{W}$$

Equation of temperature of central rotating tool core surface

$$Q = K\times A\times {dt}/{dx} \tag{3.18}$$

$$120.57 = 79.5\times 2\times 3.14\times (.2)\times (.8)\times (T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} - 30.12)/.4$$

$$T_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 30.72^{o}\text{C}$$

Equation of heat transfer of central rotating tool core surface

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = K\times A\times {dt}/{dx} \tag{3.19}$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 79.5\times 2\times 3.14\times (.2)\times (.8)\times (30.72 - 30.12)/.4$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 143.78\text{W}$$

Equation of temperature at the tool tip surface

$$Q = K\times A\times {dt}/{dx} \tag{3.20}$$

$$143.78 = 79.5\times .007\times (T_{\substack{TOOL\\TIP\\SURFACE}} - 30.72)/.07$$

$T_{\substack{TOOL\\TIP\\SURFACE}}$ = 48.80ºC

Equation of heat transfer at the tool tip surface

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = K \times A \times {dt}/{dx} \tag{3.21}$$

$Q_{\substack{TOOL\\TIP\\SURFACE}}$ = 79.5 $\times$ .007 $\times$ (48.80 - 30.72)/.07

$Q_{\substack{TOOL\\TIP\\SURFACE}}$ = 143.73W

Table 3.8 shows that at 4A magnetizing current the temperature at the tip goes above 50ºC. Due to high temperature and less viscosity it effects the finishing process, therefore the coolant coil required at 4A magnetizing current to the electromagnet. From these above calculations it has been investigated that if the coolant temperature controlled by less than or equal to 30ºC then the temperature at the tool tip surface goes below 50ºC.

3.5 Calculate temperature at tool tip surface by passing coolant at 5A

Equation of temperature of electromagnet coil surface

$$Q = K \times A \times {dt}/{dx} \tag{3.22}$$

$$Q = K \times A \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - T_{coolant} \right) / dx$$

$$200 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - 23 \right) / 0.5$$

$T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}}$ = 23.19ºC

Equation of heat transfer of electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times {dt}/{dx} \tag{3.23}$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{coolant} \right) / dx$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times (23.19 - 23) / 0.5$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 190.91\text{W}$$

Equation of temperature of central rotating tool core surface

$$Q = K \times A \times {dt}/{dx} \tag{3.24}$$

$$190.91 = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} - 23.19)/.4$$

$$T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = 24.14^{o}\text{C}$$

Equation of heat transfer of central rotating tool core surface

$$Q_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = K \times A \times {dt}/{dx} \tag{3.25}$$

$$Q_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (24.14 - 23.19)/.4$$

$$Q_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = 189.71\text{W}$$

Equation of temperature at the tool tip surface

$$Q = K \times A \times {dt}/{dx} \tag{3.26}$$

$143.78 = 79.5 \times .007 \times (T_{\substack{TOOL\\TIP\\SURFACE}} - 24.14)/.07$

$T_{\substack{TOOL\\TIP\\SURFACE}} = 48.00°C$

Equation of heat transfer at the tool tip surface

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = K \times A \times {dt}/{dx} \quad (3.27)$$

$Q_{\substack{TOOL\\TIP\\SURFACE}} = 79.5 \times .007 \times (48.00 - 24.14)/.07$

$Q_{\substack{TOOL\\TIP\\SURFACE}} = 189.68W$

Table 3.8 shows that at 5A magnetizing currents the temperature at the tip goes above 50ºC. Due to high temperature and less viscosity it effects the finishing process, therefore the coolant coil required at 5A magnetizing currents to the electromagnet. From these above calculations it has been investigated that if the coolant temperature controlled by less than or equal to 23ºC then the temperature at the tool tip surface goes below 50ºC.

3.6 Calculate temperature at tool tip surface by passing a coolant at 6A

Equation of temperature of electromagnet coil surface

$$Q = K \times A \times {dt}/{dx} \quad (3.28)$$

$$Q = K \times A \times \left(T_{\substack{ELECTROMAGNET\\COIL\\SURFACE}} - T_{coolant} \right) / dx$$

$$288 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - 13 \right) / 0.5$$

$$T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 13.28^{o}\mathrm{C}$$

Equation of heat transfer of electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.29)$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{coolant} \right) / dx$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times (13.28 - 13) / 0.5$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 281.34\mathrm{W}$$

Equation of temperature of central rotating tool core surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.30)$$

$$281.34 = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} - 14.28)/.4$$

$$T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = 15.68^{o}\mathrm{C}$$

Equation of heat transfer of central rotating tool core surface

$$Q_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.31)$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 79.5\times 2\times 3.14\times(.2)\times(.8)\times(15.68 - 14.28)/.4$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 281.34W$$

Equation of temperature at the tool tip surface

$$Q = K\times A\times {dt}/{dx} \quad (3.32)$$

$$281.34 = 79.5\times .007\times(T_{\substack{TOOL\\TIP\\SURFACE}} - 15.68)/.07$$

$$T_{\substack{TOOL\\TIP\\SURFACE}} = 49.83^{o}C$$

Equation of heat transfer at the tool tip surface

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = K\times A\times {dt}/{dx} \quad (3.33)$$

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = 79.5\times .007\times(49.83 - 15.68)/.07$$

$$Q_{TIP} = 279.44W$$

Table 3.8 shows that at 6A magnetizing current the temperature at the tip goes above 50ºC. Due to high temperature and less viscosity it effects the finishing process, therefore the coolant coil required at 6A magnetizing current to the electromagnet. From these above calculations it has been investigated that if the coolant temperature controlled by less than or equal to 13ºC then the temperature at the tool tip surface goes below 50ºC.

3.7 Find temperature at tool tip surface by passing coolant at 7A

Equation of temperature of electromagnet coil surface

$$Q = K\times A\times {dt}/{dx} \quad (3.34)$$

$$Q = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{coolant} \right) / dx$$

$$392 = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - (-4) \right) / 0.5$$

$$T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = -3.60^{\circ}C$$

Equation of heat transfer of electromagnet coil surface

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times dt / dx \qquad (3.35)$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = K \times A \times \left(T_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} - T_{coolant} \right) / dx$$

$$Q_{\substack{ELECTROMAGNET \\ COIL \\ SURFACE}} = 400 \times 2 \times 3.14 \times (.2) \times (.8) \times (-3.60 + 4) / 0.5$$

$$Q_{\substack{ELECTROMAGNET \\ COIL}} = 401.92W$$

Equation of temperature of central rotating tool surface

$$Q = K \times A \times dt / dx \qquad (3.36)$$

$$401.92 = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} - (-3.60))/.4$$

$$T_{\substack{CENTRAL \\ ROTATING \\ TOOL \\ CORE \\ SURFACE}} = -1.58^{\circ}C$$

Equation of heat transfer of central rotating tool core surface

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.37)$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 79.5 \times 2 \times 3.14 \times (.2) \times (.8) \times (-1.58 - (-3.60))/.4$$

$$Q_{\substack{CENTRAL\\ROTATING\\TOOL\\CORE\\SURFACE}} = 403.4\text{W}$$

Equation of temperature at the tool tip surface

$$Q = K \times A \times {dt}/{dx} \qquad (3.38)$$

$$403.4 = 79.5 \times .007 \times (T_{\substack{TOOL\\TIP\\SURFACE}} - (-1.58)/.07$$

$$T_{\substack{TOOL\\TIP\\SURFACE}} = 49.16^{o}\text{C}$$

Equation of heat transfer at the tool tip surface

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = K \times A \times {dt}/{dx} \qquad (3.39)$$

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = 79.5 \times .007 \times (49.16 + 1.58)/.07$$

$$Q_{\substack{TOOL\\TIP\\SURFACE}} = 403.3\text{W}$$

Table 3.8 shows that at 7A magnetizing current the temperature at the tip goes above 50ºC. Due to high temperature and less viscosity it effects the finishing process, therefore the coolant coil required at 7A magnetizing current to the electromagnet. From these above calculations it has been investigated that if the coolant temperature controlled by less than or equal to -4ºC then the temperature at the tool tip surface goes below 50ºC.

Table 3.10 Summary of calculated theoretical results for tool tip surface temperature

Magnetizing currents (A)	Tool tip surface temperature without coolant (ºC)	Tool tip surface temperature with coolant (ºC)	Controlled coolant temperature(ºC) to maintain the tool tip surface temperature below 50ºC
1A	45.86ºC	Not required	Not required
2A	48.94ºC	Not required	Not required
3A	54.21ºC	45.96ºC	≦35ºC
4A	60.78ºC	48.80ºC	≦30ºC
5A	70ºC	48ºC	≦23ºC
6A	81.83ºC	49.83ºC	≦13ºC
7A	96.58ºC	49.12ºC	≦-4ºC

Table 3.10 shows that calculated theoretical results for tool tip surface temperature. It observed that from 1A to 2A magnetizing currents the tool tip surface temperature is less than 50ºC so there is no requirement of cooling system to maintain the tool tip surface temperature. But it observed that from 3A to 7A magnetizing currents the coolant temperature controlled manually to controlled the tool tip surface temperature less than or equal to 50ºC.

Table 3.11 Comparisons of experimental and theoretical results of tool tip surface temperature without coolant

Magnetizing currents(A)	Theoretical tool tip surface when ambient temperature was considered 45°C	Theoretical tool tip surface when ambient temperature was considered 31°C as per the actual temperature during the experimentations	Experimental tool tip surface temperature when ambient temperature was 31°C
1A	45.86°C	31.93°C	32°C
2A	48.94°C	35.66°C	35°C
3A	54.21°C	41.95°C	40°C
4A	60.78°C	49.66°C	48°C

The comparison of experimental and theoretical results of tool tip surface temperature without cooling system. It observed that during calculations of theoretical and experimental tool tip surface temperature, the temperature of ambient air was 31°C. It was observed that during comparison of experimental and theoretical results of tool tip surface temperature the results were approximately same is shown in table 3.11.

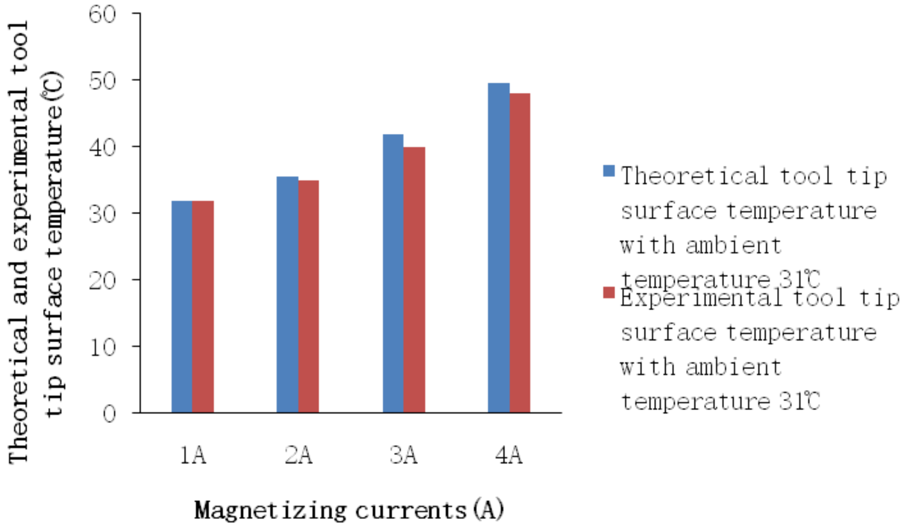

Fig 3.13 Comparison of experimental and theoretical results of tool tip surface temperature

Fig 3.13 shows the comparison of experimental and theoretical results of tool tip surface temperature. It has been observed that the experimental and theoretical results of tool tip surface temperature is approximately same.

CHAPTER 4

CONCLUSIONS AND FUTURE SCOPE

4.1 Conclusions

The conclusions related to the thermal analysis of ball end magnetorheological finishing tool is summarized as follows.

- The tool tip surface temperature was found less than 50ºC at 1 to 2A without coolant. Therefore, no cooling coil is required for performing the finishing operations at magnetizing current 1 to 2A.
- The tool tip surface temperature increased above 50ºC when magnetizing current starts increasing from 3A which affects the finishing process as viscosity of MR finishing fluid at the tool tip surface decreases above 50ºC. This slower the finishing tool performance.
- The comparison of experimental and theoretical results of tool tip surface temperature was found approximately nearer.
- The cooling coil is required to incorporate with finishing tool to control the tool tip surface temperature below 50ºC.
- The controlled coolant temperature at various higher magnetizing currents were suggested to control and maintain the tool tip surface temperature below 50ºC.
- The coolant temperature is suggested to maintain below 35ºC for magnetizing current 3A when the tool tip surface temperature as 54.21ºC.
- The coolant temperature maintained at 30ºC to control the tool tip surface temperature 60.78ºC.
- The coolant temperature maintained at 23ºC to control the tool tip surface temperature 70ºC
- The coolant temperature maintained at 13ºC to control the tool tip surface temperature 81.83ºC
- The coolant temperature maintained at 13ºC to control the tool tip surface temperature 96.58ºC.

4.2 SCOPE FOR FUTURE STUDIES

- The thermal analysis of ball end magnetorheological finishing process can be done with magnetorheological fluid.
- The thermal analysis of ball end magnetorheological finishing tool can be done by using of different types of coolants.
- The thermal analysis of ball end magnetorheological finishing tool can be done by using different materials of cooling jacket.

CHAPTER 5

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