EXAMINING THE TEMPERATURE FIELD OF ECO-FRIENDLY MQL GRINDING VIA EXPERIMENTAL RESEARCH AND FEM SIMULATION

Prashant Patil [1], Nitin Kardekar [2], Savita Shinde [3], Rahul Yadav [4] and Dhanapal Kamble [5]

[1] Professor, Department of Mechanical Engineering, AESCOET, Pune, MS, India.
[2] Associate Professor Department of Mechanical Engineering, BSCOER, Pune MS India.
[3] Associate Professor Department of Mechanical Engineering MIT WPU, Pune MS, India.
[4] Associate Professor Department of Mechanical Engineering MMM COE, Karvenagar, Pune MS, India.
[5] Assistant Director, Directorate of Technical Education Maharashtra, Mumbai, India.

Abstract

This article proposes a way to model transient heat conduction during grinding using a finite element technique (FEM). The grinding technique known as minimal quantity lubrication, or MQL, is unconventional yet safe for the environment. The minimal quantity lubrication (MQL) grinding technique and traditional grinding's temperature distribution are predicted using the FEM model. The findings of the heat transfer for an item whose heat source is moving over its surface were used to define the boundary conditions for this FEM simulation. A surface grinding machine equipped with instrumentation was employed for the examination. Water-based nanofluids are used in the MQL system at a range of concentrations. To create nanofluids, CuO and Al2O3 nanoparticles were used. The temperature of the work piece's surface and the cutting force were utilized to measure the grinding performance. The findings of the analysis show that the FEM temperature values and the laboratory temperature measurements agree rather well. At 3.2 mm from the component's front edge, the temperature is maximum. The workpiece remains at the same temperature on its surface for the duration of the grinding operation. In flood, MQL with 6% CuO, and dry grinding, the average heat transmission to the workpiece was 39.72 W/mm2, 42.36 W/mm2, and 63.23 W/mm2, respectively. This model may be used to forecast different lubrication systems' cooling efficiency.

Keywords: FEM Modelling, Surface Grinding, Nanofluids, MQL operation, Boundary Layer.

1. INTRODUCTION

Environmental friendly machining is a component of green manufacturing. Green manufacturing takes into account of economic, social and environmental factors. Cutting fluid contains chemicals that are bad for the environment. Respiratory illnesses are caused by the unhealthy mist that is produced during machining operations. Untreated used chemical coolant disposal contaminates groundwater and surface water. The decrease of energy usage is a further goal of environmental responsible machining. Since environmental damage is a by-product of all energy production techniques. Grinding is a method of surface finishing that produces an excellent surface finish with close tolerance. Because of the huge surface area of contact between tool and the workpiece, grinding takes more specific energy to remove material than other machining methods. High temperature is produced at the point where the grinding tool and the workpiece meet. High temperatures have effect of thermally damaging the work item. Phase transition, workpiece burn, residual stress, decreased fatigue strength, and fractures are examples of thermal effects in the work piece [1]. Effective lubrication and cooling are needed to minimize the negative consequences of high temperatures. Coolant transports chips away from grinding area and lubricates grinding region and prevents heat damage of the workpiece.

The cooling and lubrication of the grinding process have been extensively researched. Conventional systems use a lot of coolant, 6000ml/hr. On the shop floor, these systems provide an uncomfortable working environment. The price of recycling spent is really expensive. Two trends, dry grinding and minimum quantity lubrication (MQL) can help to decrease need for grinding fluid. Thermal damage to the workpiece occurs while using the dry grinding process. Because of this, MQL is a superior option than dry and conventional flood grinding. In the MQL system, benefits of both flood and dry grinding are included. The fluid circulation rate for the MQL is 15 -150 ml/hr, which is quite low when compared to flood grinding [2]. Compressed air serves as the cooling medium in the MQL system, while high thermal conductivity nanofluids serve as the lubricating medium. Compressed air and water-based nanoparticles were employed as the cooling medium for the MQL system. Nanoparticles have better surface area to volume ratio that's why there heat carrying capacity is higher [3]. In comparison to convectional cooling, tangential force, normal force, and wheel wear rate were found to be lessened in research on MQL performance for grinding operations. The surface smoothness and G ratio of cast iron were improved during an experimental research employing different nanofluid lubricating solutions. [4]. MQL grinding for AISI 52100 steel is more cost-effective and environmentally benign, according to De Paiva et al. [5]. For dry, flood, and MQL grinding conditions, Abrão et al. determined specific grinding energy [6].

The shear plane is where the energy from grinding is dissipated. In this concept, the shear plane was where heat was transferred to the workpiece, so some of the heat went into the chips and some of it went into the workpiece [7,8]. There has been significant research on heat transfer modelling methodologies for grinding applications, however due to temperature measurement methods, many of these studies lack experimental confirmation [9,10]. Numerous studies have been published that propose both theoretical and experimental elements in the MQL grinding of heat transfer. The conventional Jaegers approach proposes that a moving heat source flows along the outside of a semi-infinite body with a constant velocity [11]. Because they are challenging to resolve analytically, the majority of thermal issues in grinding are resolved using appropriate numerical approaches [12,13]. Researchers can forecast the surface temperature of a workpiece using computer models rather than laborious testing. FEM, or the finite element approach, has recently grown in importance as a tool to forecast temperature of the grinding zone (14,15).

The major scope of this work is to assess findings of grinding surface temperatures generated by a numerical thermal model with those acquired from an experimental model. The work piece's convective cooling is taken into consideration by the FEM. A thermal model is used for calculating temperatures of surface grinding in dry, MQL and flood situation.

2. THEORETICAL THERMAL ANALYSIS FOR THE GRINDING REGION

Three main sources of heat generation in grinding operation are friction between workpiece and abrasive grain, friction between chip and grain, the deformation of plastic along the chip-workpiece shear plane. Heat generated in grinding region during grinding is carried to workpiece by chips, grinding wheel, and oil mist. For this study, it is anticipated that heat would be produced at point where the grinding wheel and material have contact.

$$lc = (a \cdot ds)^{1/2} \quad (1)$$

Where a is cut depth and ds represents grinding wheel diameter, one may calculate length of contact at the grinding zone (lc) from equation 1.

The grinding zone's heat flux (q) may be determined using equation 2.

$$q = \in \frac{FtVs}{lc} \quad (2)$$

Where ∈ is the workpiece's heat flux %, Vs is velocity of grinding wheel, and workpiece's tangential force is Ft. Equation 3 used for computation of heat entering workpiece.

$$\in = 1 - \frac{Uch}{U} \quad (3)$$

Uch means the amount of grinding power needed to create chips. Its value is 13.8 J/mm^3 for ferrous materials and is consistent for a particular workpiece material. Equation 4 may be used to compute U, total grinding power needed for the grinding operation.

$$U = \frac{FtVs}{aVw} \quad (4)$$

Ft is the tangential force per unit width where Vw is work's speed. During the test, tangential force can be detected.

3. FINITE ELEMENT MODELLING

3.1 Geometric modelling

Cut depth impacts temperature distribution of workpiece. For sake of FEM simulation, source of the heat passing to the workpiece is assumed as a circular shape. For the purpose of studying the continuous grinding process, discretization is utilised. It makes FEM modelling easier. The "time step and sub-step method" is used to accomplish this. After each time step a thin layer of material is removed from job.

The length of time step, abbreviated as t, is ratio of thickness of chip removed at each time step and speed of table.

$$t = \frac{a}{Vw} \quad (5)$$

It is evident that when time step's duration is decreased, the simulation's accuracy grows. For a given lesser time step, simulation consumes longer duration. A shorter time step is needed for greater accuracy of simulation.

3.2 The Workpiece Meshing

The kind of component meshing will affect the length of the simulation. For simulation, dense meshing requires more time than coarse meshing. Near the grinding surface, the temperature differential is greater. In zones with significant temperature gradients, meshing should be denser for greater precision. The surface temperature gradient is mild at the bottom; therefore using a coarser mesh will speed up the simulation.

3.3 Materials of the workpiece

The thermal characteristics of testing material, such as its density, thermal conductivity, and specific heat, have a significant impact on the temperature of the grinding zone. There is complex link between workpiece material properties and temperature. The workpiece temperature while grinding is a nonlinear function of the heat flow intensity. Many researchers previously thought that workpiece material qualities were either constant or linearly related to temperature. Material property values are calculated using the polynomial interpolation approach.

3.4 Boundary circumstances

The heat source travels over workpiece surface. Due to the mobility of heat source, the boundary conditions are time-dependent. At every single stage, the thermal flux boundary condition is placed into a circular arc region. At the following time step, heat flow along the circular arc shifts to the adjunct circular arc. Simulation results from the previous time step are used for the current time step condition. Another boundary condition is coolant-induced convection cooling. The convective coefficient among the side interface, ground interface, cooling fluid, and unground interface is employed for wet, MQL grinding. The bottom surface of the workpiece has very little heat exchange; hence it is referred to as an adiabatic surface.

4. EXPERIMENTS AND MEASUREMENTS

Tests have been carried out using an instrumented surface grinding machine in order to validate the numerical and analytical results. Figure 1 shows experimental setup. The MQL system delivered lubricant at rate of flow 10 ml/min. A grinding wheel uses abrasives of average size. The grinding wheel is 160 mm diameter, 16 mm in breadth. For production of the Work material, flat EN24 plates are employed. The size of the workpiece material is 12 mm wide by 90 mm long.

Fig 1: Grinding machine experimental setup

The grinding wheel's surface speed was set at 30 m/s, with a 10μm cut depth. The surface grinding process was carried out in a single direction by a table speed of 2600 mm/min. The temperature of grinding zone is recorded by a thermocouple implanted on a workpiece. The surface roughness was measured with a profilometer.

5. DISCUSSION OF THE FINDINGS

Figure 2 depicts the three-dimensional variation in temperatures during dry grinding. Throughout the grinding, the workpiece received an average heat flux of 63.23 W/mm^2. The highest temperature that was recorded during grinding was 604^0C. Figure 3 indicates the three-dimensional variation in temperatures in flood grinding.

ISSN 1462 2815

Throughout the grinding, the workpiece received an average heat flux of 39.72 W/mm^2. 196^{0}C was the highest temperature ever recorded for flood grinding. Figure 4-6 depicts the three-dimensional variations in temperature for MQL grinding using a 2%, 4%, and 6% Al_2O_3 nanofluid coolant. During the grinding, the workpiece received an average heat flux of 44.34W/mm^2 using 6% Al_2O_3 nanofluid coolant for MQL grinding. The highest temperature recorded was 487^{0}C, 434^{0}and 415^{0}C, for 2%, 4%, and 6% Al_2O_3 nanofluid coolant.

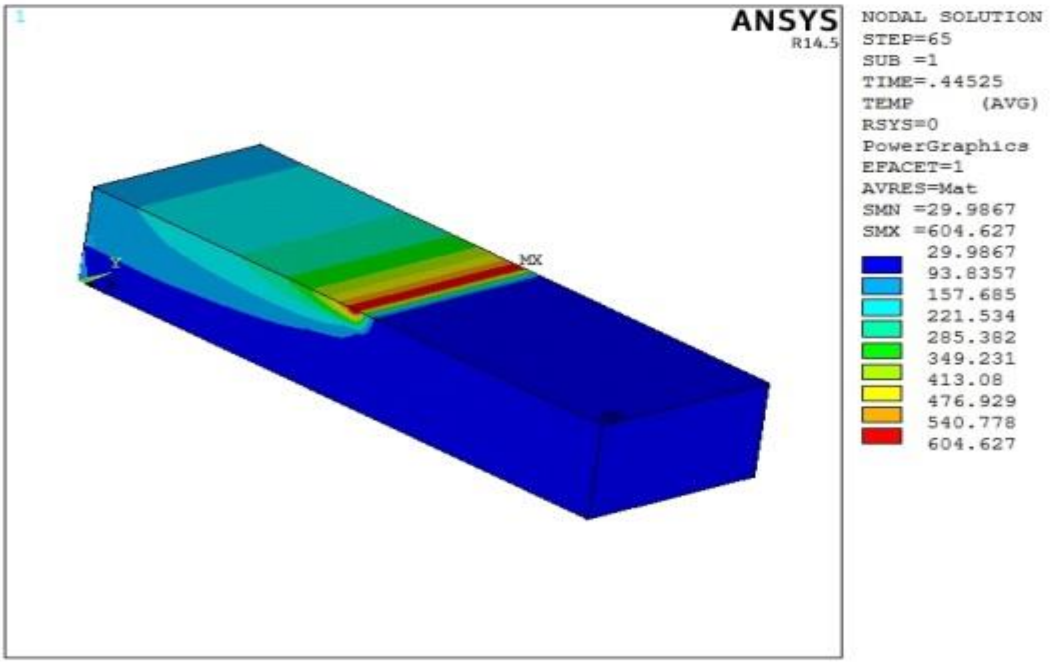

Fig 2: Temperature field for dry grinding

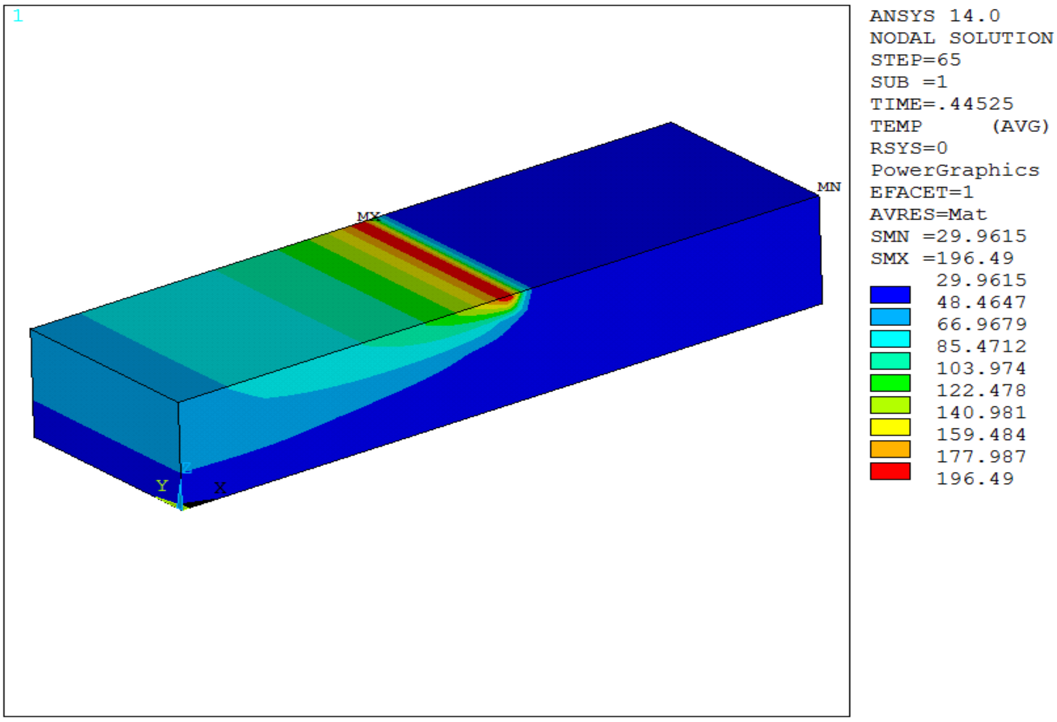

Fig 3: Temperature field for flood grinding

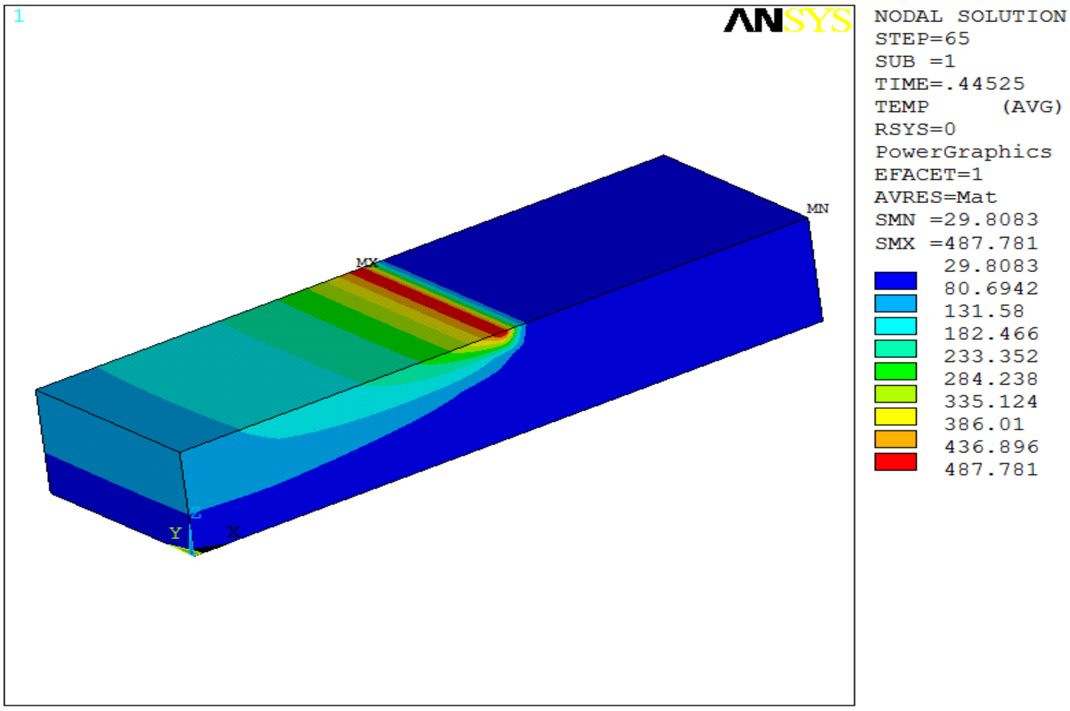

Fig 4: Temperature field for MQL grinding for Al_2O_3 2% nanofluid

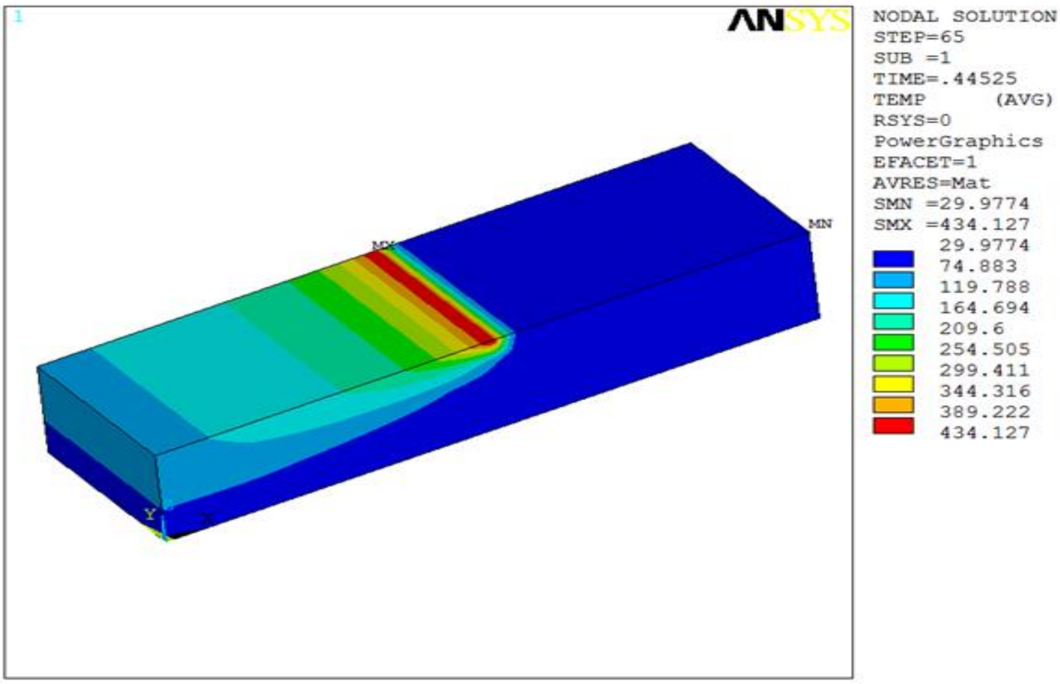

Fig 5: Temperature field for MQL grinding for Al_2O_3 4% nanofluid

Figure 7-9 displays the three-dimensional temperature fluctuations during MQL grinding using 2%, 4%, and 6% CuO nanofluid coolant. During grinding, the workpiece received an average heat flux of 42.36 W/mm^2. 410^{0}C was the highest temperature registered when using a 6% CuO nanofluid for MQL grinding. Maximum temperatures of 428^{0}C and 476^{0}C were recorded when using a 4% and 2% CuO nanofluid for MQL grinding, respectively. The highest temperature on the workpiece surface for MQL,

ISSN 1462 2815

dry, and flood grinding is compared in Figure 10. It is apparent that the greatest temperature, 604^{0}C, was recorded during dry grinding. Lowest temperature for flood grinding is 196^{0}C. Comparing MQL grinding to dry grinding, the latter produces superior outcomes. CuO 6% nanofluids recorded the lowest temperature for MQL grinding at 409^{0}C.

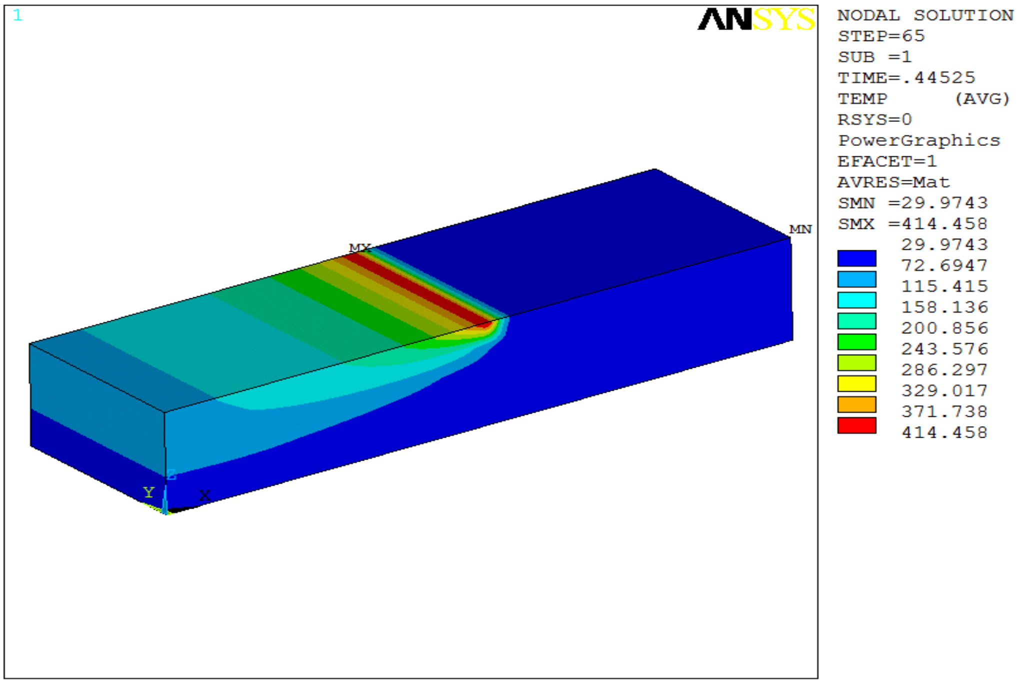

Fig 6: Temperature field for MQL grinding for $Al_2O_3$6% nanofluid

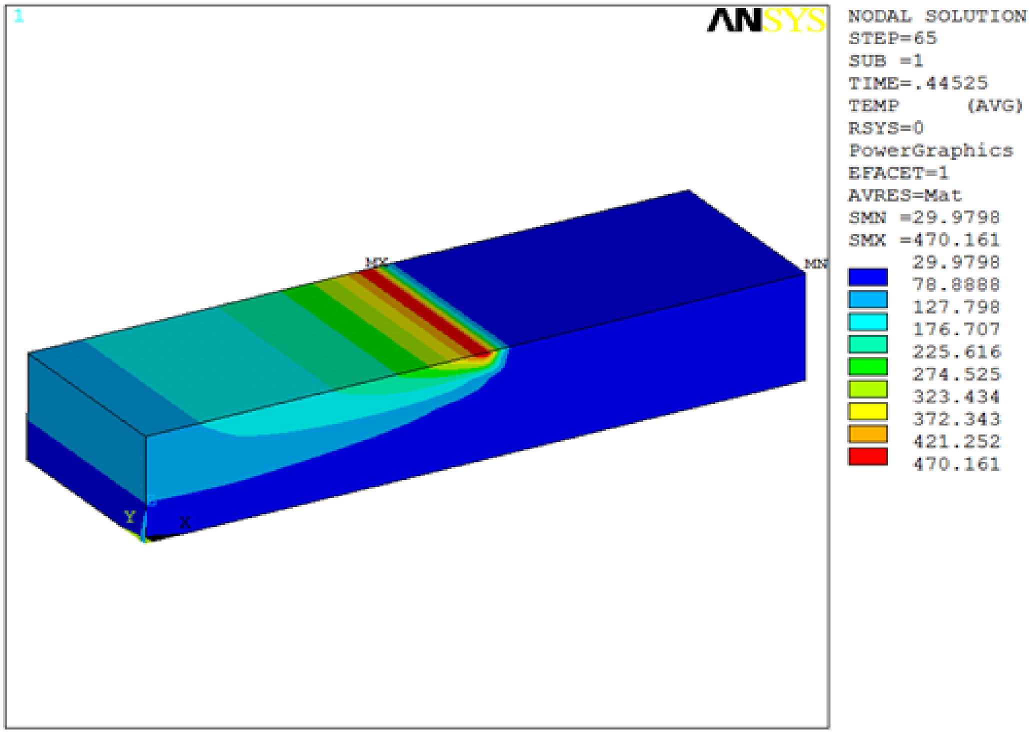

Fig 7: Temperature field for MQL grinding for CuO 2% nanofluid

ISSN 1462 2815

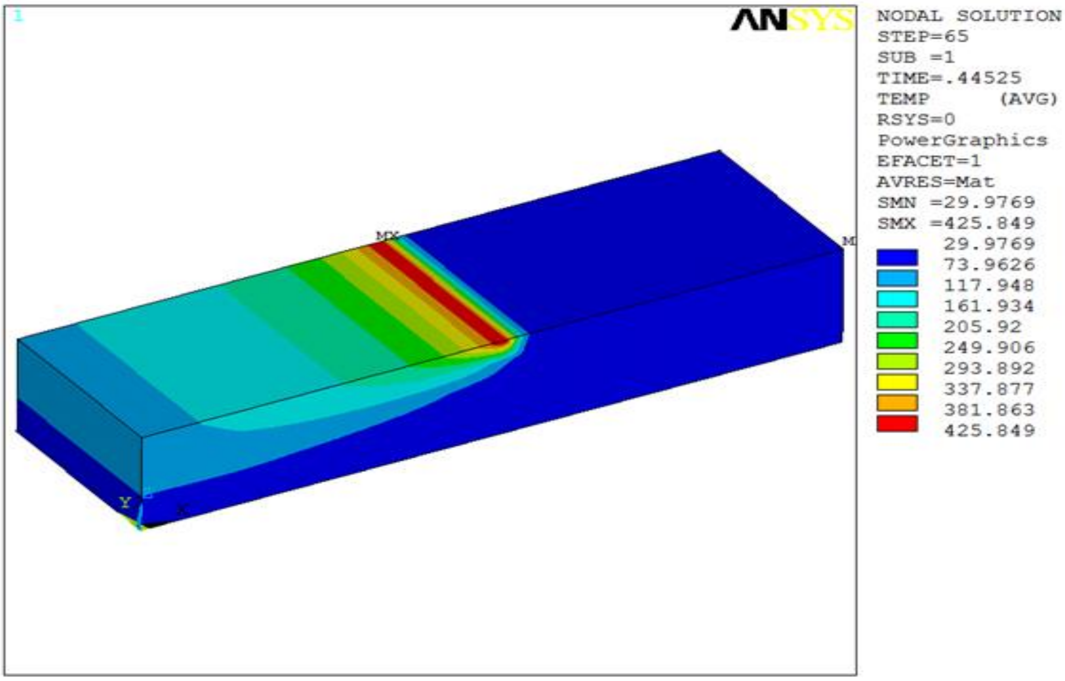

Fig 8: Temperature field for MQL grinding for CuO 4% nanofluid

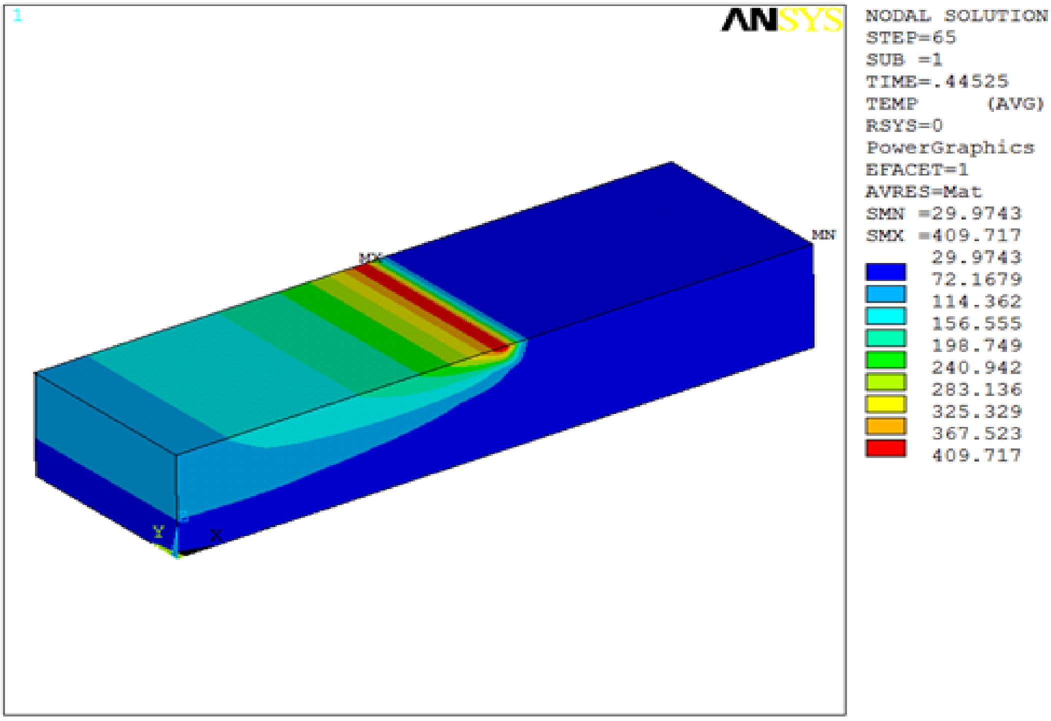

Fig 9: Temperature field for MQL grinding for CuO 6% nanofluid

ISSN 1462 2815

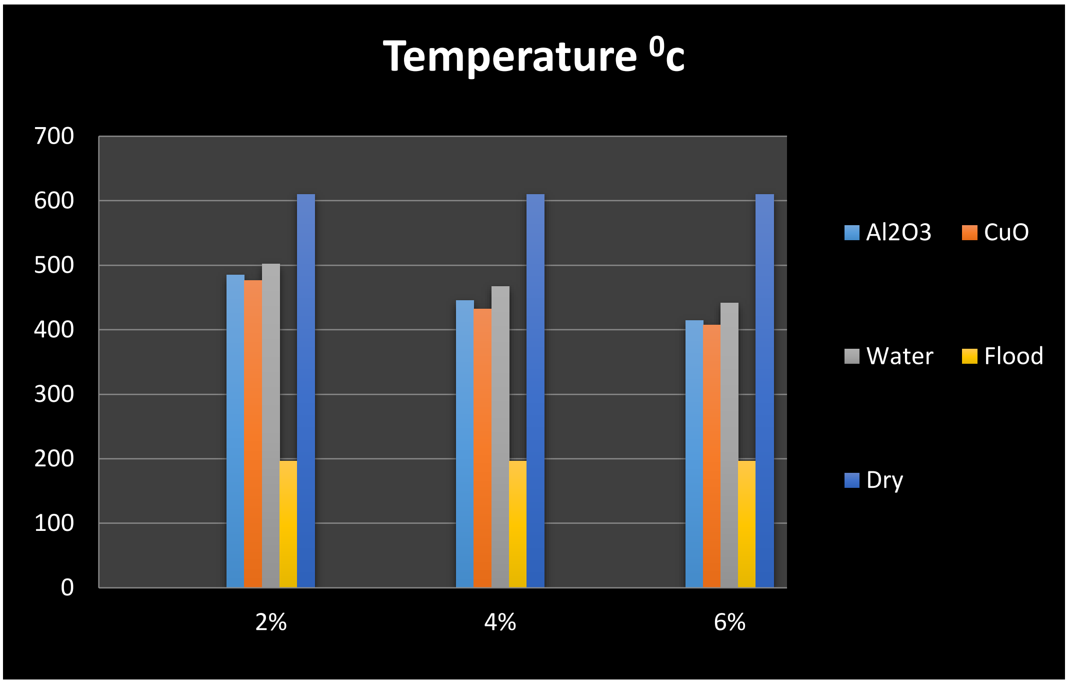

Fig 10: Maximum FEM Temperature field for MQL grinding

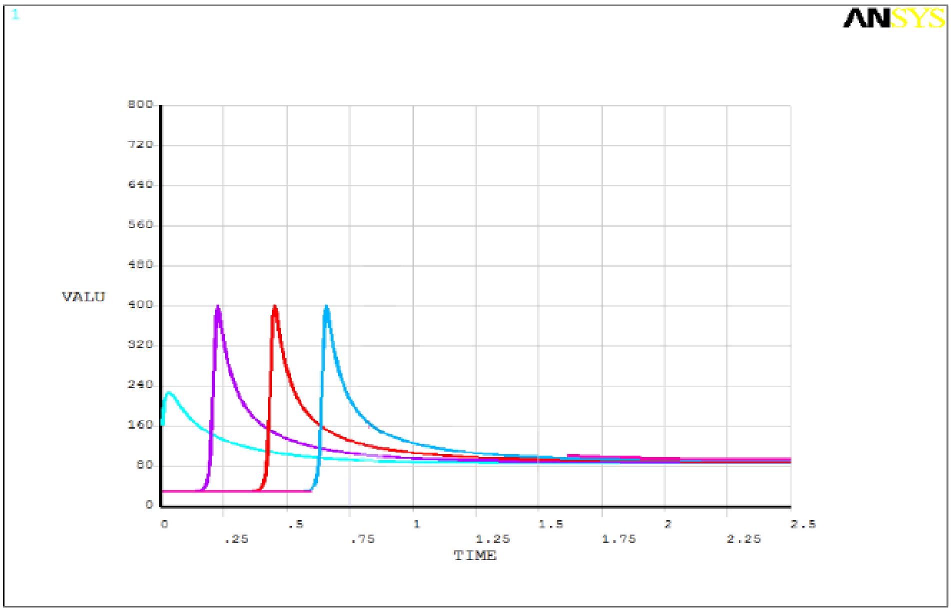

Fig 11: Temperature field for MQL grinding during various time intervals

Figure 11 displays a temperature variation over the workpiece surface interaction during various time intervals. Workpiece surface temperature is lower during the first time step of grinding and rises as work is done. After the seventh time step, the steady state for the transient temperature field was reached. The greatest temperature on the workpiece was about 409^{0}C and was found 4.3mm from the leading edge. Throughout the remainder grinding process, the workpiece's surface temperature stays constant. Figure 12 shows a comparison of empirically determined results with temperature field modelling findings for different grinding settings. The chart indicates that there is good match between the simulation findings of the temperature field and the values obtained from experimental measurement.

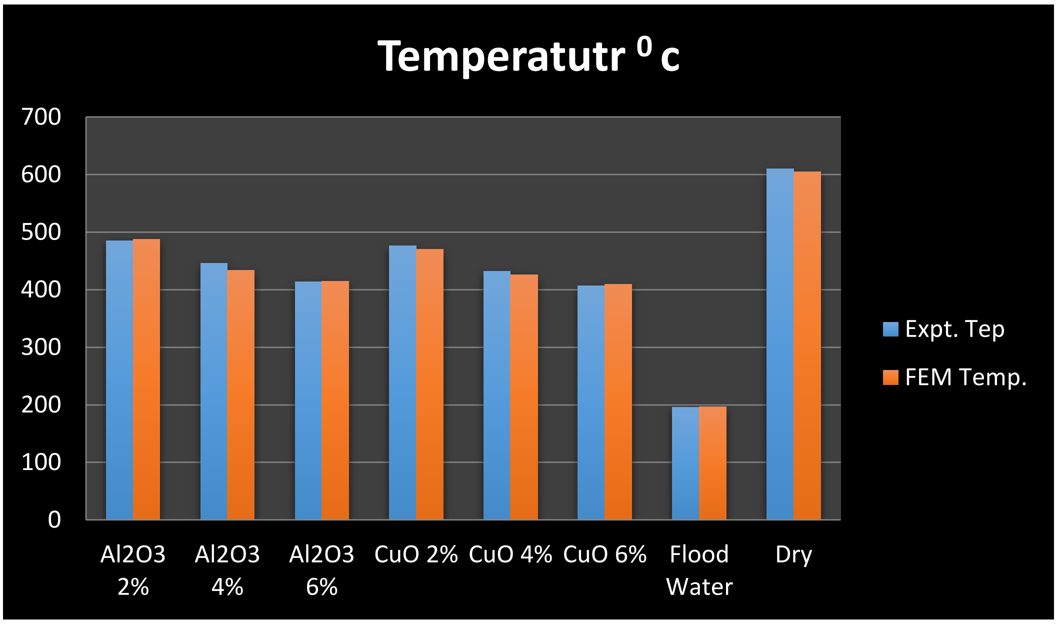

Fig 12: Comparison of experimental and FEM Temperature field for MQL grinding

CONCLUSION

The features of temperature propagation on the workpiece surface were examined, and the effectiveness of standard flood and dry grinding was contrasted with MQL grinding based on nanofluid. The numerical 3 D Finite Element method was used to simulate the temperature of the grinding zone. Three-dimensional finite element models were confirmed by using experimental data from a thermocouple system with verification. The experiment's results and theoretical findings are the sources of the following conclusions.

1) A comprehensive understanding of the grinding process may be attained with the use of the finite element model. The transient temperature field was approaching its steady state after the sixth time step. At 3.2 mm from the component's front edge, the temperature is maximum. The workpiece remains at the same temperature on its surface for the duration of the grinding operation.

2) In flood, MQL with 6% CuO, and dry grinding, the average heat transmission to the workpiece was 39.72 W/mm2, 42.36 W/mm2, and 63.23 W/mm2, respectively.

3) The maximum temperature measured for dry grinding was 6040C, while for flood grinding it was 1960C. The maximum temperature for MQL grinding in 6% CuO nanofluid was 4090C. Compared to dry grinding, MQL grinding with 6% CuO nanofluid coolant reduces the workpiece's temperature by 1950C.

4) The experimental research demonstrates that MQL grinding only partially meets the grinding cooling requirements as compared to flood grinding.

References

1) Gupta, M.K.; Song, Q.; Liu, Z.; Sarikaya, M.; Jamil, M.; Mia, M.; Singla, A.K.; Khan, A.M.; Khanna, N.; Pimenov, D.Y., "Environment and economic burden of sustainable cooling/lubrication methods in machining of Inconel-800", J. Clean. Prod. 2021, 287, 125074.

2) Majumdar, S.; Das, P.; Kumar, S.; Roy, D.; Chakraborty, S., "Evaluation of cutting fluid application in surface grinding," Measurement 2021, 169, 108464.

3) Li, M.; Yu, T.; Zhang, R.; Yang, L.; Ma, Z.; Li, B.; Wang, X.; Wang, W.; Zhao, J., "Experimental evaluation of an eco-friendly grinding process combining minimum quantity lubrication and graphene-enhanced plant-oil-based cutting fluid,". J. Clean. Prod. 2020, 244, 118747.

4) Ibrahim, A.M.M.; Li, W.; Xiao, H.; Zeng, Z.; Ren, Y.; Alsoufi, M.S., "Energy conservation and environmental sustainability during grinding operation," of Ti–6Al–4V alloys via eco-friendly oil/graphene nano additive and Minimum quantity lubrication", Tribol. Int. 2020, 150, 106387.

5) De Paiva, R.L.; Ruzzi, R.D.S.; De Oliveira, L.R.; Filho, E.P.B.; Neto, L.M.G.; Gelamo, R.V.; Da Silva, R.B., "Experimental study of the influence of graphene platelets on the performance of grinding of SAE 52100 steel," Int. J. Adv. Manuf. Technol. 2020, 110, 1–12.

6) Abrão, B.S.; Pereira, M.F.; Guimarães, C.; Da Silva, L.S.V.; Ruzzi, R.D.S.; Da Silva, R.B.; Bianchi, E.C.; Machado, A.R., "Surface Finish Evaluation of AISI P100 Steel after Grinding with MQL Technique with Different Flow Rates," J. Mech. Eng. Autom. 2020, 10, 60–65.

7) Hübner, H.B.; Da Silva, R.B.; Duarte, M.A.V.; Da Silva, M.; Ferreira, F.I.; De Aguiar, P.R.; Baptista, F.G., "A comparative study of two indirect methods to monitor surface integrity of ground components," Struct. Health Monit. 2020, 19, 1856–1870.

8) Srivastava, A.; Awale, A.; Vashista, M.; Yusufzai, M.Z.K., "Monitoring of thermal damages upon grinding of hardened steel using Barkhausen noise analysis," J. Mech. Sci. Technol. 2020, 34, 2145–2151.

9) Javaroni, R.L.; Lopes, J.C.; Garcia, M.V.; Ribeiro, F.S.F.; Sanchez, L.E.D.A.; De Mello, H.J.; Aguiar, P.R.; Bianchi, E.C., "Grinding hardened steel using MQL associated with cleaning system and cBN wheel", Int. J. Adv. Manuf. Technol. 2020, 107, 2065–2080.

10) Garcia, M.V.; Lopes, J.C.; Diniz, A.E.; Rodrigues, A.R.; Volpato, R.S.; Sanchez, L.; de Mello, H.J.; Aguiar, P.R.; Bianchi, E.C., "Grinding performance of bearing steel using MQL under different dilutions and wheel cleaning for green manufacture", J. Clean. Prod. 2020, 257, 120376.

11) Ruzzi, R.D.S.; da Silva, L.R.R.; da Silva, R.B.; da Silva, W.M., Jr.; Bianchi, E.C, "Topographical analysis of machined surfaces after grinding with different cooling-lubrication techniques|, Tribol. Int. 2020, 141, 105962.

12) Prashant Patil, Nitin Kardekar, Dhanapal Kamble, "Performance analysis and optimization of nano particle base Libr-H_2o vapor absorption system by using Taguchi, Grey relational analysis and ANOVA", Materials Today procedings, September 2022.

13) G. Singh, M. Teli, A. Samanta, R. Singh, "Finite element modeling of laser-assisted machining of AISI D2 tool steel", Mater Manuf Process, 28 (2013), pp. 443-448.

14) B. Shi, H. Attia, R. Vargas, S. Tavakoli, "Numerical and experimental investigation of laser-assisted machining of Inconel 718", Mach Sci Technol, 12 (2008), pp. 498-513.

15) A.K. Parida, K. Maity, "Numerical analysis of chip geometry on hot machining of nickel base alloy", J Brazilian Soc Mech Sci Eng (2018).