Thermal Modelling and Analysis of AISI 1055 Steel in Surface Grinding

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Grinding is commonly regarded as a final machining process in the production of components requiring smooth surfaces and fine tolerances. High tangential forces cause large amount of heat generation and concentration in grinding zone. High temperature is likely to create high residual stress on the work piece surface which is detrimental to the product. In this paper two different methods are used to measure the temperature: thermography and thermocouple method. Both the results compared and found that thermography method is more accurate and precise. The reason for this is that the thermography method gives the temperature of the surface whereas thermocouple gives temperature below the surface. In addition thermography technique gives the whole window of temperature. Here AISI 1055 steel is used as a material and several sets of experiments are performed on surface grinding machine with aluminium oxide wheel without coolant. So in order to reduce the residual stress in this paper grinding parameters such a work speed, depth of cut, etc. are investigated which in turn determine the temperature gradient experienced in the grinding zone. This work is an attempt towards determining the onset temperature limit of AISI 1055 steel. Along with this a FEA model will be developed to predict the maximum temperature for this process. Predicted results will be experimentally validated.

Keywords— : Thermography, Grinding Zone, Thermocouple, Temperature Gradient.

I. INTRODUCTION

Continuously increasing claims of the market lead to increasing requirements for the manufacturing processes like grinding. Grinding is one of the important and frequently used finishing processes that are used to produce parts with high quality and precision. Nowadays, we are using this process in almost all the industries (automobile, aerospace, transportation, medical etc.) to get high surface finish and tolerance. Moreover, this process is used to produce innovative and authenticate products. Grinding is commonly regarded as a high specific energy process as lot of heat is generated during the process. This heat is the result of the friction between the high speed abrasives and workpiece surface. Grinding temperature reaching a threshold can make the material's metallurgical structure changed, caused residual stress, grinding burn and even crack phenomenon on the workpiece surface.

Out of all these changes, residual stress is the most important changes as it directly affects the surface integrity and life of the product. Changfeng Yao et al [1] explained the effect of wheel speed and depth of cut on temperature of Aermet 100 steel in surface grinding with three different type of wheel. Here they used single alumina wheel, white alumina wheel and CBN wheel with coolant and thermocouple is used as a temperature measuring instrument. They observed that the total heat flux of single alumina wheel is the largest, which attributes to the effect of two aspects: large tangential grinding force and poor thermal properties of grinding wheel. While the heat flux to the CBN wheel is significantly higher than the other wheels, this is because the thermal property of CBN wheel is the best within three wheels. The magnitude of residual stresses originated from grinding is determined not only by the physical and mechanical properties of the material being ground, but also by the grinding parameters—wheel speed, workpiece speed, depth of cut, grinding wheel composition, lubricant, etc.—which in turn determine the temperature gradient experienced in the grinding zone [2]. An empirical relationship between the peak residual tensile stress and the maximum grinding zone temperature has been found in steels[3].

Using single step analytical models, temperature been developed and finite element analysis has been carried out to determine the temperature variation in grinding zone during surface grinding operation. This model is based on Jaeger analysis in grinding temperature distribution, in this analysis grinding wheel is assumed as heat source[4]. As, the resulting damage is thermal in nature; therefore, modeling of the heat transfer mechanisms involved in grinding is important as it may lead to improved selection of process parameters and may result in improved part quality with less waste and a lower scrap rate. There has been significant work on individual thermal modelling [5] techniques reported in the literature. Ramnatha and shaw [6] created one of the earliest thermal partition ratio models based on the workpiece and grinding wheel interaction; however, this early model had limited success due to the lack of heat transfer paths. Malkin[7]created a model for dry grinding of ferrous materials with aluminium oxide grinding wheels that has been successful for shallow grinding .However; there has been a lack of experimental validation using common temperature measurement [8]. Therefore, the focus of this is to compare the surface temperatures obtained from numerical thermal models to the surface temperature obtained experimentally by two different techniques-one by thermocouple method and other by thermal imaging camera. Moreover the effect of this high temperature on residual stress has been studied to find out the onset temperature limit of AISI 1055 steel.

II. GRINDING KINEMATICS

In order to accurately predict grinding temperatures using the thermal models one must properly define the kinematics of the grinding process. Fig. 1 shows a typical grinding process with exaggerated kinematics for clarity. There are following assumptions we made for this thermal modelling of grinding.

A. Heat source moves in a straight-line and with constant speed over the surface
B. Quasi-static circumstances
C. Half of the chipping energy is converted into heat.

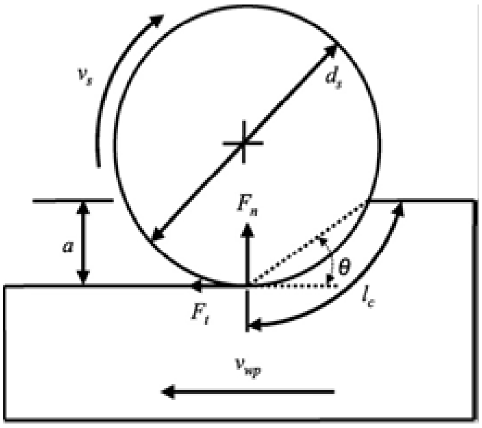


Fig. 1.Grinding kinematics

The grinding wheel of diameter d_s rotates with a tangential velocity v_s and workpiece translates with a velocity of v_w. The resulting forces from the grinding wheel/workpiece interaction are the tangential force *F*t

and the normal force *F*n, while the power consumed during the grinding process is *P* and total heat flux generated is given by-

$$q_t = \frac{P}{l_c . b_{wp}} \qquad (1)$$

As we know power is manly depends on tangential force and the velocity of the wheel so, power is given by-

$$P = f_t . v_s \qquad (2)$$

Material removal and subsequent heat generation occurs along the contact length (*l*c). The contact length depends on both the kinematics as well as the contact mechanics of the grinding process. Therefore following equation has been used to calculate the contact length as it accounts for both kinematics as well as contact mechanics.

$$l_c = \sqrt{\frac{8R^2 P d_s}{\pi \mu E v_s b_{wp}}} \quad + \quad \sqrt{a}. d_s \qquad (3)$$

But for simplification we normally neglect the contact mechanics and focussed only on kinematics of grinding so, above equation reduces to-

$$l_c = \sqrt{(a. d_s)} \qquad (4)$$

Now for calculating the temperature of the workpiece, the total amount of heat generated during each pass can be calculated with the help of spindle power. But total amount of heat produced is not absorbed by the workpiece only but by the four main heat sinks i.eworkpiece, grinding wheel, chips and coolant.

The proportion of the heat absorbed by the each heat sink is known as heat partition ratio and it is the most important parameter for accounting the temperature or heat flux of the workpiece. Now each grain performed three functions cutting, ploughing, and sliding. Cutting or chipping energy is the energy required by the grain for chipping and we assumed that half of this energy contributing to the cutting and half for heat generation. Ploughing energy is required for deforming the material plastically and no cutting takes place. Similarly whole sliding energy is contributing for heat generation as no cutting action takes place.

Now heat partition ratio is defined as the ratio of the amount of heat absorbed by the workpiece to the amount of energy generated during the process. Therefore heat partition ratio,

$$\in = \frac{.5u_{ch} + u_{pl} + u_{sl}}{u}$$

$$\in = 1 - .5\frac{u_{ch}}{u} (5)$$

Where, $u_{ch} = 13.8 {}^{J}/_{mm^3}$ for grinding all ferrous materials.

And the total amount of heat generated can be calculated with the help of spindle power,

$$u = \frac{f_t . v_s}{d . v_w} \qquad (6)$$

Therefore maximum temperature in grinding can be calculated as,

$$T_{wp-max} = \in_{wp} * \frac{\text{Total heat transferred to the work piece}}{\text{Heat transfer cofficient of the workpiece}}$$

$$T_{wp-max} = \frac{\in_{wp} . q_t}{h_{wp}} \qquad (7)$$

The above equation gives an expression for calculating the maximum temperature in grinding for all materials.Here we are neglecting the effect of heat transfer coefficient of the fluid as we are not using any coolant here so; heat transfer coefficient mainly depends on the thermal effusivity of the workpiece and the velocity of the workpiece and can be calculated as

$$h_{wp} = \frac{\beta_{wp}}{C}\sqrt{\frac{v_{wp}}{l_c}} \qquad (8)$$

Where C is the correction factor and mainly depends on a heat transfer number known as Peclet number and can be calculated with the help of grinding parameters as follows

$$P_e = \frac{v_{wp} . l_c}{4\alpha_{wp}} \qquad (9)$$

III. NUMERICAL MODEL

Numerical model was used to calculate the maximum temperature in the grinding zone. Two planar, multistep models were created using ANSYS software. One advantage of ANSYS is that it allows a parametric study, in which various solutions can be acquired for a variety of variables without the need to reconstruct the model manually when the values of the variables are changed. This feature is suitable for the present work.

A. Geometric Model

2D models are suitable for thick materials but we need 3D models for thin materials. Unlike deep grinding, shallow grinding model did not include the effect of contact angle. In analysis of heat flux in grinding there are mainly two factors that account most for temperature distribution, heat flux distribution and shape of the heat flux. The shape of the heat flux can be rectangular, triangular or any other shape following the trend of polynomial function. . Time step and substep method is used where time step is the time where the heat source is assumed to be stationary between two successive time steps. It can be calculated from the following relation-

$$\text{Time step} = \frac{elementsize}{velocityofworkpiece}$$

The full solution is obtained by incrementally stepping the heat flux along the workpiece and adjusting the boundary conditions accordingly. Element size is the main factor in FEM analysis and it depends on the contact length in grinding. If the contact length is very small then we should take smaller element size and as a result we have do analysis for small time step.

B. Workpiece Meshing

We used workpiece of length 130mm,width of 30mm and thickness of 10mm. Method of discretization is used in FEM to study the grinding process. The workpiece is regarded as two dimensional semi-infinite bodies. The dimension of the workpiece is selected such a way that the length and width of the workpiece are much larger than the grinding zone. As temperature gradient is maximum on the top surface, size of the element is more refined on the top surface and its size is decreasing as we go from top to bottom surface. Meshed workpiece is shown below-

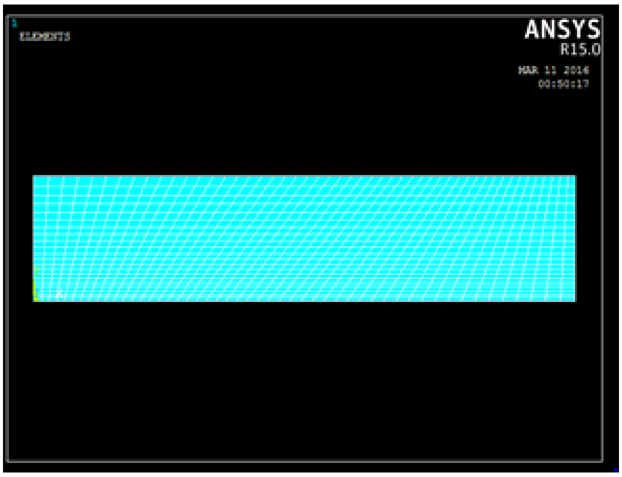


Fig. 2 Meshed workpiece

C. Boundary Conditions

As the bottom surface and the side surfaces are located far away from the heat flux zone or grinding zone, deformation is assumed to be zero here. The boundary conditions in simulation of grinding changes continuously as heat source is moving and result of the first boundary condition acts as a boundary condition of the next time step. But here we are using a constant boundary condition as we are assuming that the heat flux is stationary on a particular node. As we are not using any coolant fluid so for upper and side surfaces we can take air as a convective fluid. Initial temperature of the workpiece is taken as 25 ^{o}C.

IV. EXPERIMENTAL APPARATUS

The experiments are performed on a surface grinding machine with aluminium oxide grinding wheel without using any coolant. Temperature measurements are done by the two different methods one with the thermocouple and other with the thermal imaging camera. The experimental set up with embedded thermocouple in the material is showing in the fig.

A. Selection of Material

AISI 1055 steel is used as a workpiece material and white aluminium oxide as a grinding wheel. British Standard BS En9 (AISI 1055) is a Plain medium carbon steel and chosen because of its industrial use for stress critical situations.

A chromelalumel k type thermocouple is used to measure the temperature in the first stage. Chromel acts as anode and alumel acts as cathode, this type of thermocouple can measures the temperature up to 1000 ^{o}C. Diameter of this thermocouple wire is 3.5 mm and a hole is embedded on the material of diameter 5 mm. As lot of heat is generated during grinding process and it can damage the thermocouple wire so, glass wool is used as an insulating medium. Workpiece embedded with k type thermocouple is shown in the figure.

Fig. 3Experimental setup

Table. 1 Properties of AISI 1055 steel

PROPERTIES	VALUE
Tensile strength, ultimate	660MPa
Tensile strength, yield	560MPa
Modulus of elasticity	190-210GPa
Poisson's ratio	0.27-0.30
Hardness, Brinell	197
Thermal expansion coefficient	11µm/m^{o}C
Thermal conductivity	49.8W/mK

Table.2Chemical composition

B. Thermal Imaging Camera

A thermal imaging camera is used to measure the temperature in the second stage. It is from Flir System Company having a response time of about 2 ms in the spectral band of wavelength 3 to 5 µm. In this band, the luminance has the advantage to be quite important in the range of 0 to 1000^{o}C. Moreover in this range the air is supposed to be transparent to infrared rays. Finally, the dimension of the measured window is an array of 320×255 pixels equivalent to a zone of 0.85cm×0.68cm that gives us a spatial resolution of about 26 µm per pixel.

Fig. 4 Workpiece with embedded thermocouple

V. RESULT AND DISCUSSION

Various experiments are conducted to provide a broad range of process parameters for dry grinding. The experiments are conducted at a larger depth of cut varies from 0.01mm to 0.006mm at a constant wheel speed of 26.39m/sec. The feed of the workpiece also varies from 5.2m/min to 10.75m/min and temperature measured by thermocouple and with the help of thermal imaging camera. The various parameters are shown in the table.

A Simulated Results

Based on the surface grinding condition simulation is done by ANSYS software. Basically there are three steps involved to solve this problem. These steps are pre-processor, solution of the linear equation and postprocessor. All required parameters are given as input in pre-processor step. Type of element is also selected in this step, tetrahedron element is selected for this work. One pass of grinding completed in 0.7 sec. and the whole process is divided in to 70 steps of time so that each time step is of 0.01 sec. For this time interval heat flux is assumed to be stationary on a node and by iteration temperature distribution is obtained

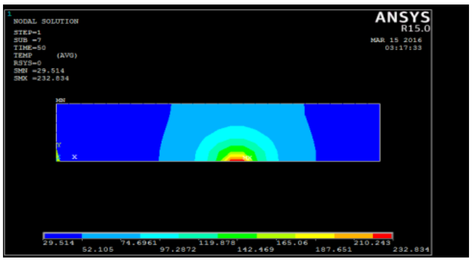


Fig. 5

Here minimum temperature temperature we found around 30^o C and maximum temperature is about 233^{o}C. Heat flux is applied at the middle of the surface and we found that temperature is maximum at the point where abrasives touches the workpiece.

The figure represents the variation of temperature with the distance from the heat flux zone. Temperature is reducing as the distance from the heat source increases. Initially the temperature is decreasing with lesser rate and the slope of the curve is quite high but after some particular distance rate of decrement of temperature is increasing due to high convective heat transfer rate.

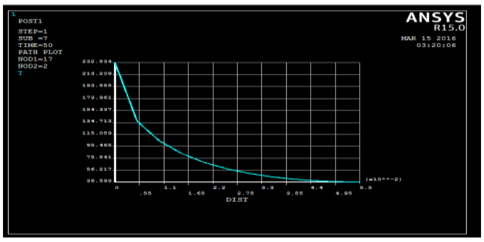
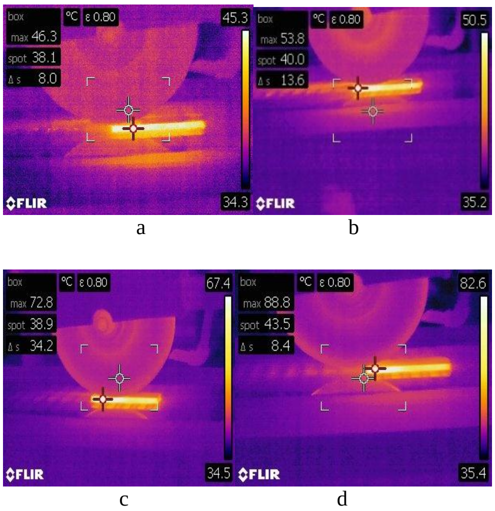


Fig. 6

BEFFECT OF GRINDING PARAMETERS ON TEMPERATURE

a. EFFECT OF DEPTH OF CUT ON TEMPERATURE

We measured the temperature in the grinding zone at the wheel velocity of 26.39m/sec and at a feed rate of 5.2m/min. Depth of cut varies from 0.01mm to 0.006mm. Initially we measured the grinding temperature with the help of a thermocouple embedded on the workpiece and after that with the help of Infrared thermal imaging camera. Thermal images at these process parameters are shown below.



a b

c d

Fig. 7Thermal images of work piece at f = 5.2 m/min and v_w of 26.39 m/s at (a)d=0.01(b)d=0.02(c)d=0.04(d)d=0.06

CHEMICAL COMPOSITION	PERCENTAGE (%)
Iron(Fe)	98.4-98.9
Manganese(Mn)	0.6-0.9
Carbon(C)	0.5-0.6
Sulphur(S)	0-0.05
Phosphorus(P)	0-0.04

Table.3Experimental process parameters

Here we can see that whole field of temperature is available, workpiece along with the grinding wheel. As we increasing the depth of cut from 0.01mm to 0.06mm temperature is also increasing from 46^{o}C to 90^{o}C.If we plot a graph between depth of cut and temperature for both thermocouple and thermal imaging camera readings we obtained the following type of curve.

This graph represents the variation of temperature with the depth of cut for both thermocouple measurements and infrared camera readings. Depth of cut varies from 0.01mm to

0.06mm; temperature varies from 35ºC to 65ºC in the case of thermocouple and 45ºC to 90ºC in the case of thermal imaging camera. In this graph, we observed that difference between the two readings is almost same up to the depth of cut 0.02mm and after that deviation is increasing. The reason for this is that as the depth of cut increases more abrasives participate in grinding process and the rate of temperature increment increases.

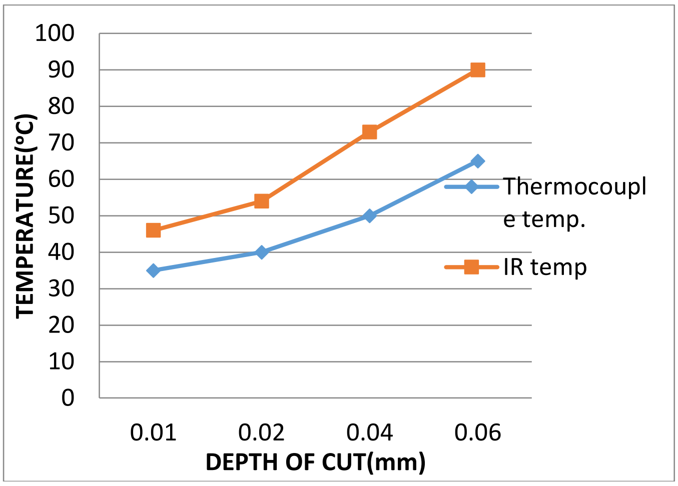
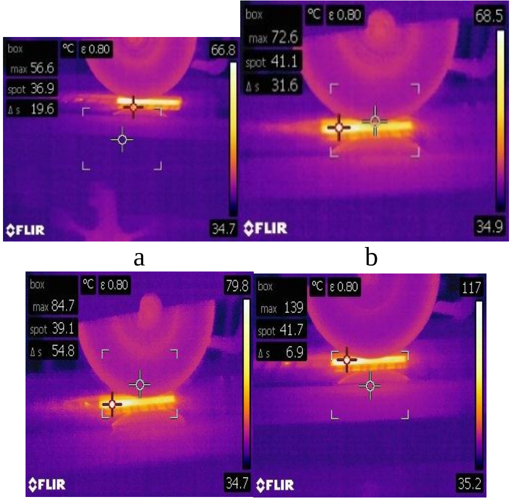


Fig. 8 Variation of temperature with depth of cut

The figure.10 shows the thermal images of workpiece at wheel velocity of 26.39m/sec and feed rate of 7.8m/min. These images showing the temperature variation throughout the whole workpiece and also the maximum temperature induced on the workpiece.

If we plot a graph of maximum temperature obtained by these thermal images and maximum temperature obtained by thermocouple following type of curve we obtained As we increased feed from 5.2m/min to 7.8m/min, the effect of depth of cut on temperature dominates more. We also observed that deviation between the two readings increases drastically after a depth of cut of 0.04 mm.Fig.11 showing the variation of temperature with depth of cut at maximum feed.



a b

c d

Fig. 9 Thermal images of work piece at f = 7.8 m/min and v_w of 26.39 m/s at (a)d=0.01(b)d=0.02(c)d=0.04(d)d=0.06

Here we observed that the difference between the two measurements is maximum. Maximum temperature obtained is about 100ºC by thermocouple and almost 190ºC by thermal imaging camera

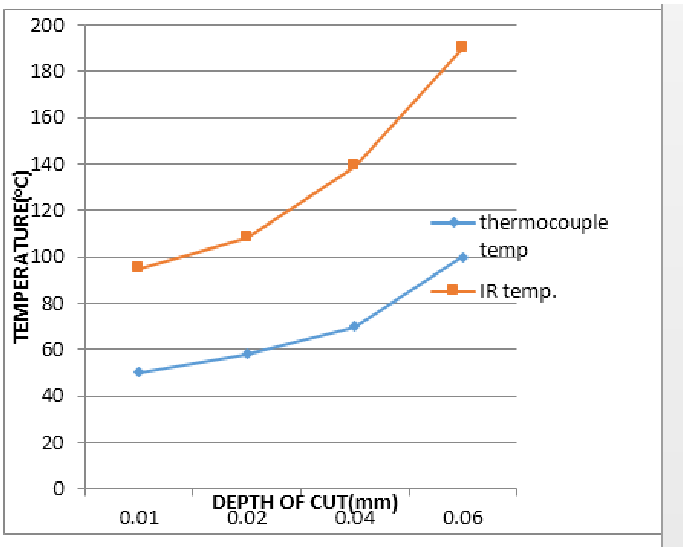


Fig. 10 Variation of temperature with depth of cut

From a [illegible] s increasing as depth of cut is increasing and maximum temperature obtained is about 190ºC at wheel velocity of 26.39m/sec, feed of 10.25m/min and depth of cut of 0.06mm. The reason for this is as the depth of cut increases, more material will adhere on the grinding wheel and it increases the frictional force between the grinding wheel and workpiece. So more heat flux is generated in the grinding zone and it results in increase in temperature.

b. *Effect of Feed on Temperature*

In the figure we can see that as the feed of the workpiece is increasing temperature is also increasing. This is because as the feed of the workpiece increases more friction occurs between the wokpiece and grinding wheel. It means more heat generates and heat flux is more for higher work feed so, temperature is increasing with increase of work feed. In the above figure maximum temperature is obtained at work feed of 10.25 m/min and minimum temperature obtained at work feed of 5.2 m/min moreover maximum temperature obtained is about 200 ºC.

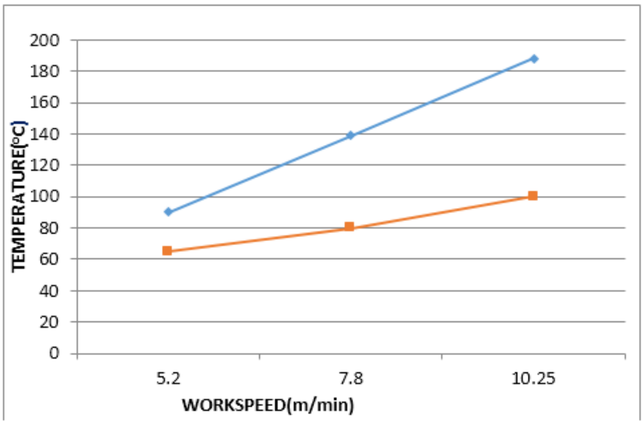


Fig. 11 Variation of temperature with workspeed

VI .CONCLUSIONS

- Maximum temperature is measured with the help of thermocouple and thermography technique separately.
- Temperature measured by thermocouple is always less than that of thermography technique as thermocouple gives the temperature 1mm below the surface. Thermography technique is better than thermocouple technique as it gives whole window of temperature on the surface. Moreover it is more consistent and reliable.
- The temperature in grinding increases continuously as depth of cut increases. It is because for large depth of cut large specific energy is required for cutting.
- The temperature in grinding increases with increase in work speed or feed.
- Two dimensional temperature variations on workpeice can be calculated with the help of finite element method. Maximum temperature obtained is 239°C.
- A mathematical model has been developed to predict the maximum temperature in the grinding zone and validated by the experiments.

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