An Investigation of Need and Potential Device For Real-time Temperature Measurement During External Cylindrical Grinding

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Abstract

The paper investigates temperature measurement techniques used so far and their limitations. A potential device along with mathematical procedure for the real-time temperature measurement in external cylindrical grinding is investigated. The research has shown various ill effects of temperature on the overall properties of most metals under machining. Great deal of work has been done to optimize the machining process. Researchers from around the globe have come up with many techniques for temperature control during machining yet, study have shown that, least work is done on temperature measurement techniques compare to temperature controlling techniques especially in rotating components. Need & potential set up of such a device was identified. Use of the Law of Electrical conductivity was explored on component under test for estimating temperature based on conductivity or resistance values. Temperature prediction and database generation was carried out which was further deployed in actual device and using Heisler charts temperatures in the component under study was determined successfully without stopping its rotation while CNC grinding. All types of instrumentation which would be essential to make such device were investigated systematically. External cylindrical grinding operation was considered for the experimentation on Hardened specimen of EN31 steel.

Keywords: *Temperature, Measurement, steel, Electrical Conductivity, Resistivity, Rotating Component, CNC Grinding*

1. Introduction

It has been long known fact that, when a steel is subjected to higher temperature its surface properties tends to deteriorate as a consequence, chances of failure before expected life goes up. The situation presented an opportunity to investigate a effect coolant while machining to control the heat generation. In recent times, significant rules and regulations are imposed by government organization on excessive use of coolant, which brings forth a new concept of Minimum Quantity of Coolant/Lubricant (MQL). It indeed is a fascinating concept but, one cannot randomly decide amount of coolant that needs to be poured while machining to control temperature. The amount of coolant is fairly proportional to the amount of heat generated. Earlier research showed that, not many devices exist which shows real-time time temperature of a component under machining especially in external cylindrical grinding. For the reason a set up was made and installed in order to identify potential deployment of such a device which can show temperature of rotating component under machining without stopping the process.

Grinding is the commonly known and extensively used finishing process. It is usually deployed in scenario such as 1) Rough Finishing wherein material up to few mm is to be removed and 2) Finishing Process in which, material in microns is removed from the component surface. The material removal takes place because of abrasive action between grinding wheel and the workpiece. While the surface grinding is in progress, very fine sized chip is removed off the surface. It was found during earlier research that, heat generation in this type of chip removal is more since, the chips are scratched off the surface by pure friction than cutting action like in single point cutting tool.

There are numerous factors which plays vital role during grinding, those factors includes, depth of cut(doc), speed of grinding wheel, type of wheel, speed of rotation of the workpiece etc. Though each one of these factors can be effective measured during the process yet, the amount of heat generation on real-time basis remains a tough nut to crack for many researchers and practitioners. Temperature measurement is important because unwanted distortions in surface and its properties were observed in many studies. One more side effect of excessive temperature growth is oxidation at the surface, surface tends to absorb a fair amount of carbon which changes its composition and surface may become brittle.

At present, the devices available for temperature measurement are divided into two categories i.e. Contact type and Non contact type. Next to none effective methods are available in contact type temperature measurement including Thermocouple, Thermistor etc in particular when workpiece is set at very high rotation speed. Contact type presents hurdles because there are always difficulties of connecting probe for temperature measurement onto rotating component. Non contact type temperature measuring devices includes, infrared gun, Pyrometer, Radiation Thermometer, etc. although these devices are available, these digital devices are hard to use on shop floor and inside the machine close to cutting zone. The reason is that, many times, actual zone where cutting is happening is not reachable so easily for detection. In another such situation one may need to monitor the temperature during machining but while coolant is ON, the actual temperature of component was found undetectable as coolant obstructs the path of detection. The limitations presented opportunity to investigate any potential device to do temperature measurement using numerical method along with some sort of contact type measurement.

With these key elements identified, the investigation was done in which, temperature was mathematically calculated using values derived from actual experimentation. Detailed procedure was established which is discussed further.

2. Literature Review

Study conducted by I. Dehri et al. [1] found out the influence of temperature on mild steel. The researcher found that, in presence of some specific compounds containing sulphur, the metal is susceptible to corrosion quicker and at comparatively lower temperature. Compound like those which could potentially promote corrosion are sometimes in the poor quality of the coolant. Other side effect is that, vapours of the coolant inhaled by the operator of machine tend to get into human lungs causing severe health issues. These are couple of ill effects of excessive coolant usage on component. If that has to be controlled, heat generation needs to be controlled in the component. The foresaid situation encourages search for temperature measuring device which further down the line can be used to not only control temperature but also facilitate the deployment of minimum quantity coolant/lubricant technique.

In grinding process, Heat generation is well known problem. Literature categorizes this temperature generation at two fronts, a background temperature and a local temperature. In grinding process, the local temperature rises due to deformation and friction taking place at the interface between grinding wheel and the workpiece under machining. On the other hand, the background temperature rise is a result of the collective influence of many local heat sources.

The background temperature has detrimental effects on the workpiece from within, whereas the local temperature rise due to excessive friction and heat generated at the grain/workpiece interface augments wearing away of the cutting grains. In order to have decent tool life from economical standpoint, The optimisation of the grinding process become must and for that excellent understanding of sources and controlling method of both these temperatures is prerequisite.

Barczak L. et al. and Hadad M. et al. conducted research involving implementation of advance cooling techniques like, MQL. The researchers used background temperature as a performance indicator to validate the effectiveness of Minimum Quantity Lubrication technique against mist jet cooling.[2][3] Another similar study to optimize the grinding hardening process using dry air and liquid nitrogen was carried out by Babic D. et al and Nguyen T. et al. in which major drawback detected was temperature measurement. Study did not reveal the method to measure the background temperature practically or mathematically.[4][5] Often software results only were used as a real temperature.

An overview of the previous research has shown many scientists and researchers attempting innovative methods of temperature controls. One of such methods includes use of nano fluids. Eastman et al. attempted two primary types of nano fluids namely, metallic and non metallic for efficient heat transfer. In that study, Metallic nanofluids consisted of copper (C_u), ferrum (Fe), gold (Au) and silver (A_g), and for non-metallic types aluminum oxide (Al_2O_3), copper oxide (C_uO) and silicon carbide (SiC) were investigated. Study showed great results with use of metallic compare to non metallic nanofluid with certain exception subjected to machining parameters.[6] Critical limitation of the study is that, to be able to use metallic or nonmetallic particle in the coolant, one must use flood cooling. If mist cooling is used, particles would block the noozle. This method doen not allow use of MQL which in long run could be devastating for the operator.

Couple of attempts has been made so far for contact type temperature measurement. In one of the study, a thermocouple was inserted in the workpiece up to known depth. When the component with embedded thermocouple was subjected to machining, the components heats up and the heat transfers to the thermocouple occurs. That reading is then used to estimate the temperature. Though this technique was effective for surface grinding, yet, it may not be always possible to drill a hole in a workpiece to measure the temperature. Alternatively, researchers also have used grindable thermocouples. This are the type in which, thermocouple wears out along with the component providing necessary temperature details. This approach is especially quite useful when drilling a hole is not possible. [7][8] But, shrinking profits of many industries, it is not recommendable to suggest deploying method which would consume the thermocouple making it useless for next experiment.

At first, these two systems may appear effective; however there is an inherent flaw in both the methods. When a component is rotating at high rpm say e.g.

4000 rpm electrical connections poses limitations of using thermocouple for temperature measurement.

In non contact type, non accessibility of area of interest for temperature measurement was the issue. The problems such as these demand an alternative solution for temperature measurement.

With such a tremendous efforts put forward by world leading scientist, still most of their research is based on simulation data. These studies exposed need for a device or a systematic approach which can assist in estimating the temperature on real-time basis.

3. Aim of Research and Proposed Solution

Aim of the research was to investigate if it is possible to create a device or set up that would permit basically,

- Real-time Temperature Measurement of rotating Component without stopping its rotation.
- Temperature at any diameter from centre should be detectable

Through rigorous literature survey a method was identified which could be tested for such a device. It was based on laws of electrical conductance. There are two fundamental laws of physics for electrical conductance. Those states that, for any metal that is a conductor, the resistance of the conductor increases linearly with temperature to certain extent. For any non conductor or semiconductor, the resistance decreases with increasing temperature.

This law if practically infused to a device, the preliminary research has shown that can be invented for real-time temperature measurement. But before the investigation can be conducted, there are quite a few numbers of unknown elements that must be addresses to.

3.1 Key Elements Identification

For successful designing and development of a device for temperature measurement based on two laws stated earlier, there were few mandatory necessities that need to be satisfied. Those includes

- Method to use component itself to be used for current conduction without shorting the circuit.
- Designing attachment to connect wires to transfer the current into rotating component.
- Blocking all unwanted path of current flow to have closed loop circuit.
- Determination of power supply capacity.
- Resistance change determination along with temperature rise.
- Other electronic hardware essential for temperature measurement and data collection.

Upon further investigation and studying various electronics literature basic road map and design for the device was prepared which is discussed further.

4. Proposed Set up For Temperature Measurement

Figure below shows the experimental arrangement that had to be used for the successful testing of the theory. As shown in the Fig.1, If external cylindrical grinding is considered, First task was way to attach fixed cable to rotating component without allowing wire to rotate along with it. The problem can be overcome by deploying simple bearing in the casing. Bearing are made up of steel and the current can pass through them easily. Ball bearing usually maintain point contact between inner race and outer race so, instead of that, if roller bearing are used, line contact can be established which provides better area for current flow.

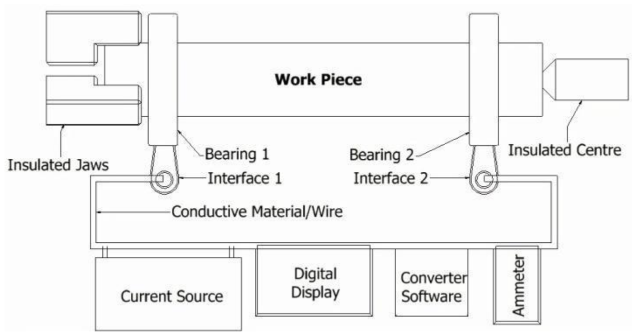

Fig.1 Circuit Diagram of Proposed Set up

Next element to tackle was creating closed loop circuit and preventing current leakage to all probable direction. Principally there were 3 paths from where current can leak 1) From Head stock or Jaws 2) From tail End 3) Through Coolant on Machine bed. First two directions can be easily blocked by simply using insulating jaws and tail end as demonstrated in figure. Rubber, plastic sheets or wood can do the trick. For the 3rd direction some customization is essential. By placing plastic bucket during earlier experimentation temporarily the current leakage can be prevented. With these solutions, current would pass through component back to source providing closed loop circuit.

Once the closed loop is obtained, current can enter in the metal component through bearing, As current is an analog signal, it must be converted to digital form. Hence, an Analog to digital converter is essentially needed. Upon conversion the signal is fed into the microcontroller. Microcontroller plays a role of comparing the resistance value and then converting it into the equivalent temperature after some mathematical steps. The conversion is obtained by programming a microcontroller in that manner.

An analogy between a resistance thermocouple and the steel work piece behavior was essential to obtain the temperature. Liner relation obtained via numerous trials can provide adequate relation among resistance, temperature and current. Controller drives a Driver IC which in turn shows reading on digital display.

Precaution must be taken that, to measure the current flow at room temperature, the resistance of steel component must be measure at that temperature must be noted. All other element such as wires, bearing, and surrounding temperature certainly influences the overall resistance of a system. All the readings must be carefully noted and added to increase the accuracy.

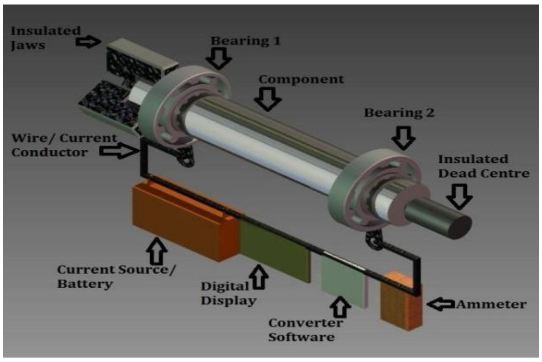

Fig.2 3D View of set up

5. Initial Experimentation & Validation of Theory

The initial investigation before manufacturing and assembling entire set up was conducted. The entire set up was made but without rotating component for earlier testing of theory. The research was carried out on the Mild Steel Rod of 15mm radius and 300mm length as shown in image below. Earlier testing have shown that, harness needed to be increased therefore the component was subjected to the induction hardening up to the harness value between 60 to 80 HRC was obtained.

Fig.3 Test Specimen Mild Steel Rod

The Specimen had a reduced diameter at the middle of length in order to control the cross sectional area available for the electrons to flow. The pre-test set up building included need of a source of heat. In actual testing with complete set up, when the rod would be subjected to external cylindrical grinding, the friction and cutting action are the main source of heat. In an attempt to initial testing of theory, the source of heat was replaced with the gas burner. The theory proposed includes finding the analogy between resistance value at different temperature of component and resistance of reference in this case PT100 thermocouple.

5.1 Resistance at different temperatures

Before the experimentation the theoretical and practical value of resistance was obtained for the said specimen as follows,

Resistivity (ρ) Value for component with Properties Similar to AISI 4140 steel was 222 x 10^{-9} Ω - m. The relation between resistivity and the resistance is given as,

$$\rho = \frac{(R \times A)}{L} \quad \text{....Eq. 1}$$

Where,

R : Resistance of Metal in ohm (Ω)
A : Cross Sectional Area Available for Current in m^2
L: Length of Interest in m
With Known dimensions of specimen we get,
A = $_4$D ^{2} = 0.00706 m^2

From Design Data book, the increase in resistivity along with increasing temperature was available as a reference for AISI 4140. Those were as follows, and by inserting those values in Eq.1 value of resistance theoretically & practically was calculated as tabulated below.

Sr. No.	Temp (T) in ^{0}C	Resistivity (ρ) in Ω - m	Calculated Resistance in Ω x 10^{-3}	Measured Resistance in Ω x 10^{-3}
1	20	222 x 10^{-9}	0. 09433	0.08763
2	100	263 x 10^{-9}	0.11175	0.10856
3	200	326 x 10^{-9}	0.13852	0.12956
4	400	475 x 10^{-9}	0.20184	0.18592
5	600	646 x 10^{-9}	0.27450	0.25689

Table1 Calculated Vs Theoretical Resistance

Resistance was practically measured using, Fluke 8508A 8 1/2 digit Multimeter. The comparison would assist in estimating at what temperature, how much resistance is to be expected.

5.2 Source of Heat at Early Stage of Research

Complete test set up with standard gas burner as a source of heat for earlier research instead of heat generated by grinding is shown in image below. It's a stationary set up. For insulation, cardboard was used as there was no coolant involved.

Fig.4 Initial test set up for theory validation

5.3 Importance of Analogy and its use in study

A DC power supply was used. The voltage of 3.5V was supplied to the set up. As the steel rod was heating up, more than hundred reading were taken for next 20 min. The readings were used to compare reading taken for the same duration but with PT 100 thermocouple. PT 100 was chosen because, It also behave in the same manner as that of steel rod i.e. positive temperature coefficient. A positive temperature coefficient A.K.A. PTC implies the characteristic of a metal to have increasing resistance along with increasing temperature. The analogy between readings effectively suggested the temperature of the rod without directly measuring it.

The analogy plays a vital role in this experiment as, earlier attempts of temperature sensing through non contact type had failed. Comparing some sort of common output from completely different materials in investigation was only concrete solution in the experimentation. Graph below shows the behavior of PT 100 used for gathering temperature vs resistance value. Reading were taken for 270 different values varying from 30^0 C to 300^0 C. These reading were used as a database for further experimentation.

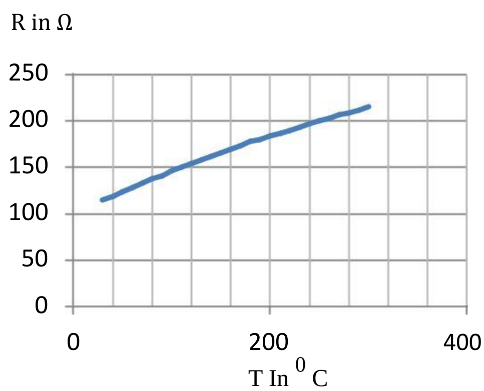

Fig.4 Temperature Vs Resistance PT100 Graph

6. Testing & Case Study

Fig.5 Actual Fanuc External cylindrical grinding CNC Machine

Various test parameters used during the testing were as

- Component : AISI 4140 Steel
- RPM of Component : 1000 rpm
- RPM of Grinder : 3000 rpm
- DoC Per Pass : 0.2 mm
- Number of Passes : 20
- Microcontroller : 8051
- Component Hardness : 73 HRC

6.1 Case Study

For better understanding how, aforementioned set up can be used for temperature measurement in cylindrical rod at any diameter a case study was conducted.

A component under study has some specific parameters which are received from Manufacturer those are radius of the Rod 15mm, thermal conductivity value (k) was 18.3 w/m^{0}C, coefficient of heat transfer (h) between surface of component and air was 120 W/m^2 ^{0}C. For determining the effectiveness of method, it was assumed that, temperature exactly at surface of the component to be identified. In this situation firstly, Characteristic length and the Biot number had to be determined. Unsteady state transient heat conduction is taking place for that Mathematical Model is as,

Mathematical Model:

To get the temperature at the surface, there are certain parameters which were calculated in advance, those includes following steps.

Step I :

Characteristic Length (Lc) : $\frac{R}{2}$ = 0.0075 m

Step II:

Biot Number (Bi) : $\frac{hLc}{K}$ = 0.0491 (Unitless)

Step III :

The above information obtained now, can be used in coordination with Heisler Chart for temperature in cylinder.

To use Heisler chart we need specific ratios which were,

1. $\frac{r}{R}$= Ratio of Radius at which temperature is to be determined to radius of component. For experimental investigation it was,
   $\frac{r}{R} = 1$

2. Inverse of the Biot number was calculated as it was essential to read the Heisler chart
   $\frac{1}{Bi} = 20.36$

Step IV :

Obtain the value of temperature ratio from Heisler chart as shown below,

$$\frac{T-Ta}{Te-Ta} \qquad \text{.....Eq. 2}$$

Where,
T- Surface temperature in ^{0} C
Ta – Atmospheric Temperature
Te – Temperature Obtained by proposed Experiment

From Heisler chart as shown below, the value of Eq.2 was obtained as 0.9675. From Eq. 2 known terms were atmospheric temperature (Ta) which was measured as 30 ^{0} C at the time of experimentation. Te is obtained by the method mentioned in this paper through analogy. Component was subject to machining and after 3 passes of 0.2mm each, resistance change was measure using high precision multimeter which was close to 148 Ω. From earlier experiment it was known that, if resistance is around 150 Ω temperature was close to 110 ^{0} C. This is how proposed method gave very crucial value to put in Eq. 2. By substituting all these values in the equation we further get surface temperature i.e. at 15mm from centre,

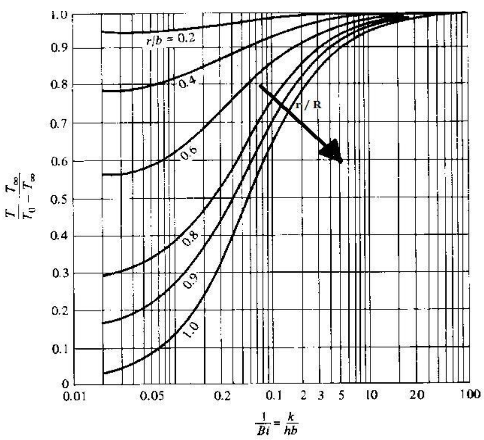

Fig.6 Heisler Chart for Cylinder [9]

$$\frac{T-Ta}{Te-Ta} = \frac{T-30}{110-30} = 0.9675$$

Therefore, Surface temperature T = 107.4^0 C.

This is how; the temperature of the component under machining can be effectively calculated that too, at any radius as long as experimental results are available to put into the Heisler Chart equations for unsteady state transient heat transfer.

Result Chart

Following Chart Represents temperature values obtained at different radii of cylindrical workpiece which was not possible with touch type of temperature measuring method.

Radii @ which temp. is to be measured in meters	Avg. Temp. Obtained of Workpiece by Analogy in degree Celsius	Actual temp. at that radius in degree Celsius
0.015	110	109.1
0.014	112	109.1
0.013	114.5	110.9
0.012	116.3	115
0.011	117.2	114.4
0.010	118	114.1
0.009	118.3	116
0.008	119.2	115.3
0.007	121.6	119.1
0.006	123	122.6
0.005	125	124.8

Conclusion

The experimentation conducted in order to understand and overcome the problems in temperature measurement along with validation of the theory transpired some key outcomes which are as follows

- Temperature measurement can be effectively done with the proposed method. Temperature at 10 different radii was successfully identified for 10 different component temperature values.
- Temperature on the surface was lower compared to the inner temperature or average temperature determined by the experiment because, surface area was not stationary it was rotating at 200 rpm. Grinding wheel was also rotating at 1500 rpm. Sufficient air flow was produced because of this motion. This allowed heat to escape to atmosphere hence slight various in the temperature existed.
- Knowing temperature at any location MQL techniques can be implemented in future.

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