JJMIE

Volume 8 Number 2, April. 2014
ISSN 1995-6665
Pages 82 - 93

Jordan Journal of Mechanical and Industrial Engineering

A Study of Experimental Temperature Measuring Techniques used in Metal Cutting

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Abstract

From the beginning of machining of materials, rise in tool, chip, and work piece temperature remains a problem for engineers. The excessive rise in temperature severely affects the tool life and the quality of the work piece. To check this issue, engineers and scientists are tirelessly investing their efforts. Measurement of the tool, chip, and work piece temperatures takes a vital breakthrough in this direction. Several methods are developed and tested from time to time. But none is found perfect, some are better at a certain situation but fails at another. The appropriate technique for a given problem depends on the situation under consideration, such as the ease of accessibility, situation dynamics, desired accuracy, spot size, and economics. These techniques are broadly categorized in three categories, namely analytical, experimental, and finite element methods. Experimental is more practical, and more accurate among these three anchors. In this paper, all experimental techniques for the measurement of tool, chip, and work piece temperatures distribution are studied in depth and presented in a user friendly concise manner.

Keywords: *Temperature Distribution, Metal Cutting, Cutting Variables.*

1. Introduction

During metal cutting, cutting parameters like optimum cutting speed, subsurface deformation, metallurgical structural alterations in the machined surface, and residual stresses in the finished part, each depends on maximum temperature, temperature gradient, and the rate of cooling at various points of tool and work piece. Not only this, the tool life, the development of new tool material, and other advances in manufacturing technology also depend on temperature rise and heat generation at three zones of heat generation. Thereby, it is often desirable to have an estimation / prediction of the generation of heat and the temperature rise at various points of tool, chip, and work piece, so that various parameters can be adjusted optimally beforehand to improve machinability.

Foundation of estimation of heat generation due to mechanical work was laid by Rumford [1]; further strengthened by Joule [2] by finding the mechanical equivalent of heat. While the application in metal cutting was first reported by Taylor [3], since then scientists and researchers have been developing various methods and techniques to estimate the temperature variations at various points of tool, chip, and work piece. These methods can be categorized in three broad categories, namely experimental, analytical, and finite element analysis-based methods. Each one has its own merits and demerits. In this paper all the experimental techniques for the measurement of heat generation (temperature rise) during metal cutting at tool and work piece, available in the relevant literature, are studied critically and presented in a user-friendly concise manner under the following subtitles: (i) Thermal paints technique; (ii) Thermocouple techniques -Tool-work thermocouple technique, Transverse thermocouple technique, and Embedded thermocouple technique; (iii) Infrared radiation pyrometer technique; (iv) Optical infrared radiation pyrometer technique; (v) Infra-red photography; (vi) Fine powder techniques; and (vii) Metallographic methods.

2. Study of Various Techniques

In 1798, Rumford's boring cannon experiment for detection of frictional heat generation proved that mechanical work can be converted into heat. This experiment laid the foundation of experimental analysis of mechanical equivalent of heat. However, no attempt was made to measure the mechanical equivalent of heat numerically. Over more than half a century later the mechanical equivalence of heat was successfully established by Joule [2] by envisioning a calorimetric method. Taylor and Quinney's [3] study of the generation of heat accompanied by plastic strain strengthened the concept of mechanical equivalence. They measured the temperature of various specimens under tensile test during

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the formation of creep and they found that the major amount of plastic energy, used for deforming the specimen, gets converted into heat. In metal cutting application, Taylor [4] studied the relation between cutting velocity and tool life, and developed a tool life equation. He also invented a tough, wear resistant, heat resistant, and hard tool material (HSS) which is still in use. Since then, scientists and researchers have been developing various methods and techniques to estimate the temperature variations at various points of tool, chip, and work piece. These methods can be categorized in three broad categories, namely experimental, analytical, and finite element analysis-based methods. Here, developments in the experimental techniques for the measurements of the temperature rise (heat generation) during metal cutting are explained with the help of self-explanatory flow charts and tables. Articles [5-19] may be referred for finite element analysis and analytical methods.

2.1. Thermal Paint Technique

This is one of the simplest and most economical techniques used for the measurement of temperature at various points (Figure 1) of tool. The technique was used by Schallbroach and Lang [20], Bickel and Widmer [21] among others. Particularly, Okushima and Shimoda [23] used this technique to determine the temperature distribution at joints of the tool. Rossetto and Koch [24] investigated the temperature distribution on the tool flank surface and developed the isotherms of temperature at various points with respect to flank surface distance in x and y direction at a specified cutting variable, as shown in Figure 2. The results obtained with this technique are generally considered approximate and confirmation of results from any other technique is recommended.

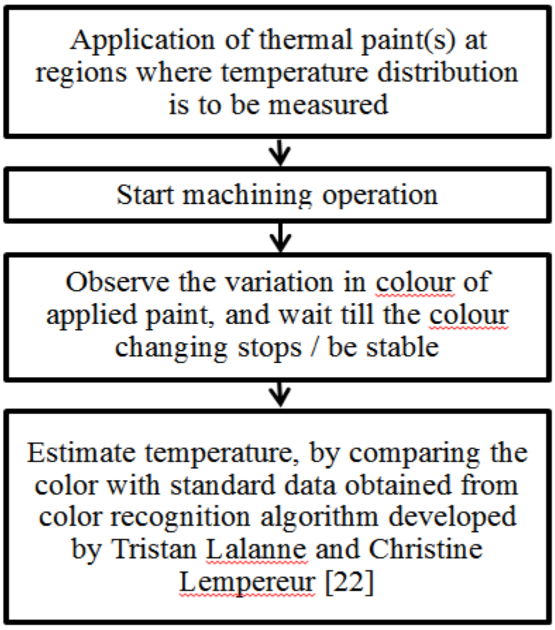

Figure 1. Process flowchart of thermal paint technique

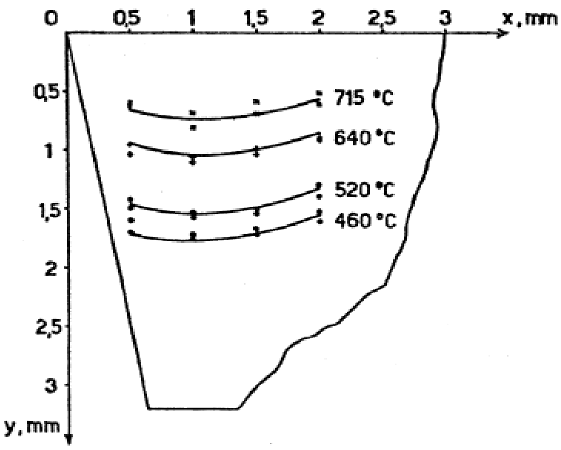

Figure 2. Experimental data and corresponding isotherms, work material: AISI 1040 steel; tool: cemented carbide (P20); depth of cut: 2 mm; feed: 0.428 mm/rev; cutting speed: 3.33 m/s [24]

2.2. Thermocouple Techniques

The technique is based on Seeback effect. According to this effect, temperature difference produced between hot and cold junctions of two dissimilar metals produces voltage difference between the junctions [25]. This voltage difference is calibrated to measure temperature rise at cutting zones [26]. This method is useful to relate various cutting parameters (speed, feed, and depth of cut) to the variation of temperature. Advantages of using thermocouples for the measurement of temperature include its simplicity, easiness of measurement, flexibility, and low cost. Stephenson [27] predicts that this method gives very good results when tungsten carbide tool insert is used in single point tool operations. Moreover, Stephenson mentions that this method is inappropriate for rough cutting at high speeds. There are basically three types of thermocouple techniques as shown in Figure 3.

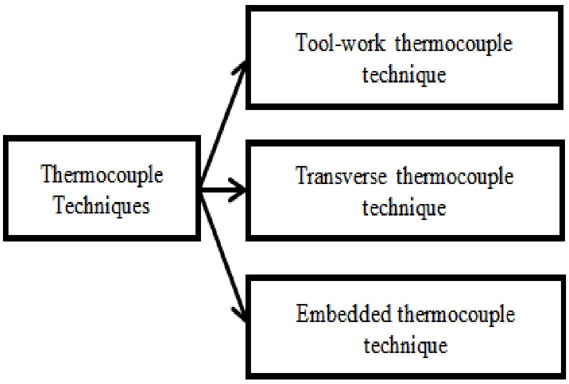

Figure 3. Types of thermocouple techniques

2.2.1. Tool-Work Thermocouple Technique

The arrangement of this technique is very simple; setup is illustrated in Figure 4 and the process is charted in Figure 5. Shaw [28] predicts that the method is easy to determine the temperature variation on tool work piece interface during metal cutting. Accurate calibration of the tool and work piece materials as a thermocouple pair is difficult. The summary of work carried out on the technique is tabulated in Table 1. The temperature rise at single point of tool can be observed by this technique. Further, the technique is widely used in case of tool inserts. In order to find the temperature rise distribution at various points of the tool, this technique could not be used in single setup.

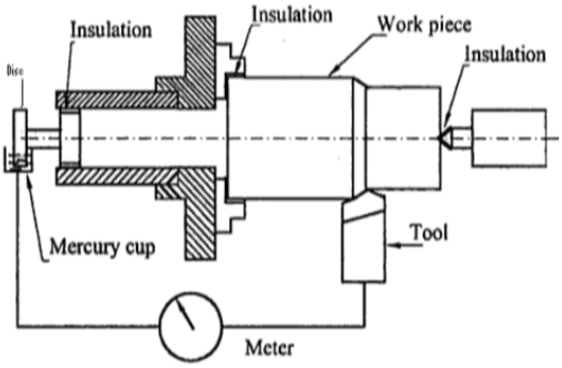

Figure 4. Schematic experimental setup for measuring average chip-tool interface temperature using tool-work thermo-couple technique [29]

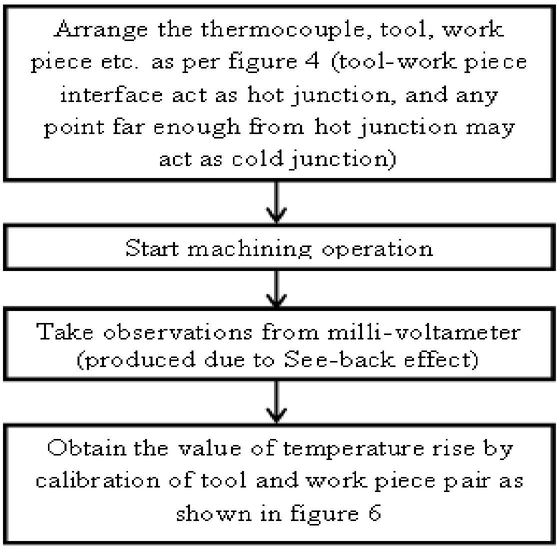

Figure 5. Process flowchart of tool Work Thermocouple Technique

Table 1. Summary of major works on tool-work thermocouple technique

S. No.	Scientist	Work material	Tool material	Conclusion
1	L.B.Abhang and M. Hameedullah [12]	EN31 steel alloy	Carbide	1. With increase in the value of cutting variables (velocity, feed and depth of cut), temperature increases 2. With increase in nose radius, temperature decreases
2	Trigger [13] Grzesik [14]	AISI 1045 AISI 304	Carbide	Increase in cutting speed, cutting forces & temperature decreases
3	S.K. Chaudhary G.Bartarya [15]	EN 24 steel	HSS (10% Co)	Increase in cutting speed and feed rate cutting zone temperature increases
4	Federico Reginalot et al. [16]	Hardened steel	Multilayer coated carbide	Temperature near the rake face increases significantly when the depth of cut changes from 0.2 to 0.4 mm.
5	B. Fnides et al. [17]	AISI H11 steel treated to 50 HRC	Mixed ceramic tool	Results are similar to the results as obtained by Federico et. al. [16]
6	H. Ay and Yang [18]	Copper, cast iron, aluminum 6061 and AISI 1045 steel	Carbide	1. More oscillations in temperature in ductile material in comparison to hard machining materials. 2. With increase in cutting variables, temperature increases. 3. With increase in nose radius, temperature decreases.

2.2.2. Transverse Thermocouple Technique

The tool-work thermocouple technique is used to measure the average temperature at tool work interface, but the temperature variation at different points and faces of the tool is difficult to analyze with this method. To overcome this problem, transverse thermocouple technique was developed by Arndt and Brown [36], which is capable of notifying temperature at various points on the tool with the help of a moving probe as detailed in Figure 7. In this technique, a high speed steel tool and cemented carbide probe or vice versa are used. The results obtained by Arndt and Brown are given in Figures 8, 9, and 10.

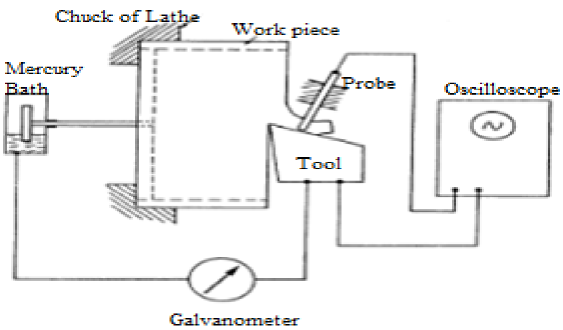

Figure 7. Experimental setup for transverse thermocouple technique, used to cut AISI 1011 steel at a cutting speed of 0.762 m/s. [36]

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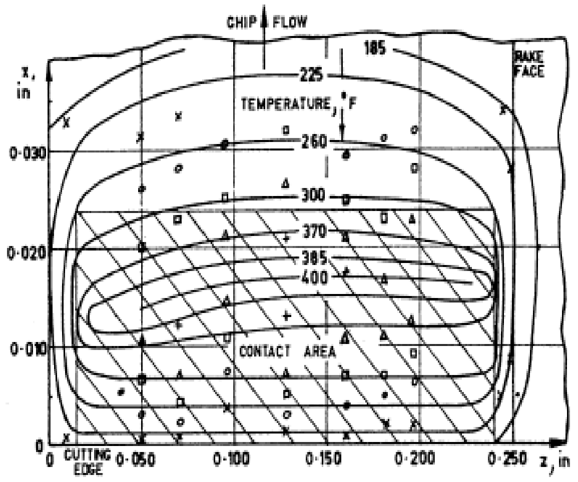

Figure 8. Temperature isotherms on rake face [36]

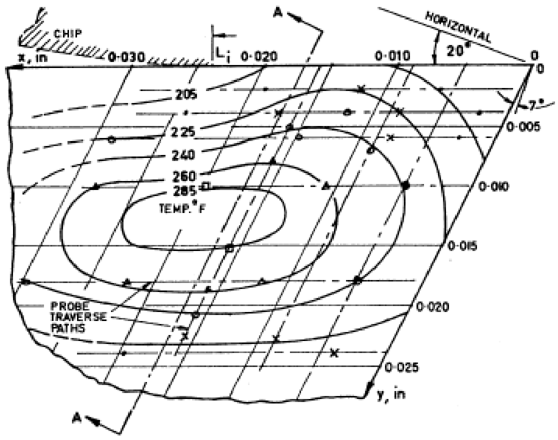

Figure 9. Temperature isotherms on end face [36]

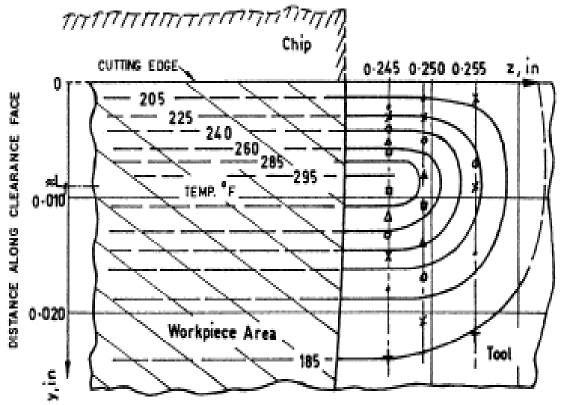

Figure 10. Temperature isotherms on clearance face [36]

2.2.3. Embedded Thermocouple Technique

In operations like milling, grinding, etc., where other two thermocouple techniques do not work, embedded thermocouple can serve the purpose. The experimental setup is illustrated in Figure 11a, and the process is given in Figure12. Yang *et al*. [37] used 9 K type thermocouples along all three surfaces of the tool for temperature measurement. Kitagawa *et al*. [38] created a micro thermocouple between an alumina- coated tungsten wire and the carbide inserts. Sullivan and Cotterell [39] measured the temperature in the turning of aluminum 6082-T6 by using two thermocouples in the work piece. Ren *et al*. [40] evaluated the cutting temperatures in hard turning of titanium alloy and chromium hard facings using thermocouples located between the tool (PCBN) and its shim. Nee *et al*. [41], Rowe *et al*. [42], Batako *et al*. [43], Lefebvre *et al*. [44] and Fang *et al*. [45] used foil / work piece embedded thermocouple technique for measuring temperatures of tool and work piece in grinding process. This type of thermocouple minimizes chances of fire hazards and measuring errors in high speed dry cutting of magnesium alloys. Hirao [46] devised a wire thermocouple setup to measure the temperature in the flank face of the tool. Similar setup was made by Black *et al*. [47] and Dewes *et al*. [48].

To overcome major problems of the only measurement of mean temperatures with which it is difficult to predict wear, fracture, etc., associated with of the embedded and single wire thermocouples, a new device – a thin film thermocouple – was proposed by Shinozuka *et al*. [49; 50]. Similar innovations were also carried out by Weinert *et al*. [51] and Biermann *et al*. [52]. This modified setup enabled temperature measurement to be close to the working zone. However, this method suffered from the problem of insufficient adhesion (between the metal coatings and the cutting inserts).

The temperature of surface cannot be measured directly while it could be estimated by extrapolating the graph. But sometimes the extrapolation of the graph is difficult as in the case of hyperbola (Figure11c). To tackle this problem, the graph may be plotted in log-log graph paper, as shown in Figure 11d. The technique has short response times of the order of 10 μs.

The major work on the technique is summarized in Table 2. The limitations of the embedded thermocouples technique include the following: (i) Temperature of surface cannot be measured directly while it could be estimated by extrapolation; (ii) Drilling of large number of holes may result in wrong results due to uneven distribution of temperature; (iii) In some cases, it is difficult and costly to drill holes, such as ceramics, cemented carbides, and hardened HSS tools; (iv) Thermocouples have limited transient response due to their mass and distance from the points of intimate contact.

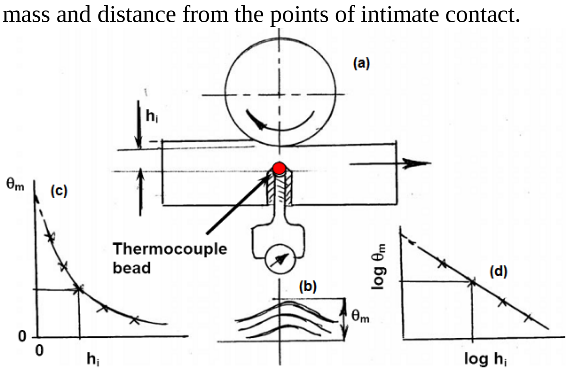

Figure 11. (a) Experimental setup of embedded Thermo-couple technique;

(b) Variation of temperature with respect to distance during machining;

(c) Variation of temperature with respect to height h_i on a simple graph;

(d) Variation of temperature with respect to h_i on a log-log graph [53]

Table 2. Summary of major works on embedded thermocouple technique

S.No.	Scientist	Investigation	Conclusion	Remarks
1	Chao et al [21]	The temperature variation at various points for various polymers by deforming them at different strain rates	Measurable temperature rise for low to medium strain rates	Failed to apply this technique successfully for measurement of temperature variation at higher strain rates
2	D. Rittel [22]	Transient temperature changes in three different polymers subjected to high impact velocity	Developed experimental results of temperature variation with reference to different strain rates	The results show that this technique can be applied for other materials
3	Rall and Giedt [23]	Tool-chip interface temperature using HSS tool (0^0 and 15^0 back rake angles)	Plotted temperature variation at different points at the interface by extrapolation on log-log graph	--
4	Qureshi and Koenigsberger [24]	Temperature variation at various surface points of the tool	Found the maximum cutting temperature was not at the cutting edge but at some distance away from it	--
5	Kusters [25]	Temperature variation of cemented carbide tool over the entire surface area of the tool with in a distance of 0.2mm from the surface of the tool	Isotherms on the surface of tool were plotted by using extrapolation method	Nearby 400 holes were drilled on the surface of cemented carbide tool, 30Mn4 steel was used as work piece at a cutting speed of 1.58m/s

2.3. Infrared Radiation (IR) Pyrometer Technique

It is a photo electric effect [59] based technique, designed and developed by Schwerd [61] and Kraemer [62], respectively. It can measure the temperature along the shear zone and tool flank accurately as shown in Figure 13. The technique was further modified by Lenz [63] by reducing the exposure time of radiations to PbS cell, so that measurement could be taken along clearance face.

The process is briefly explained in Figure14. Since the resistance of the PbS cell is sensitive to the changes in its ambient temperature as well as to the infrared radiation, to take care of this, the cell was kept at a constant temperature in an ice bath. The major work on the technique is summarized briefly in Table 3.

Table 3: Summary of major work on infrared radiation pyrometer technique

S. No.	Scientist	Operation	Region of interest	Tool / work material	Observation
1	Mayer and Shaw [31]	Grinding	Ground surface of work piece	Al_2O_3 grinding wheel / AISI 52100 steel	1. Plotted surface temperature variation with chip thickness 2. Plotted surface temperature variation with wheel speed
2	Reichenbach [32]	Planing	Shear plane, flank surface	-	For application of the method minimum temperature is 232^0C, hence the complete isotherm cannot be plotted
3	Chao et. al. [33]	Turning	Flank surface	AISI 1018 and AISI 52100 steel	1. Increasing feed or speed results in an increase of tool flank temperatures 2. A gradual shift of the maximum temperature away from the tool edge
4	Lenz [34]	Turning	Clearance face	-	Established isotherms for the clearance surface of the tool (with a little modification in setup)

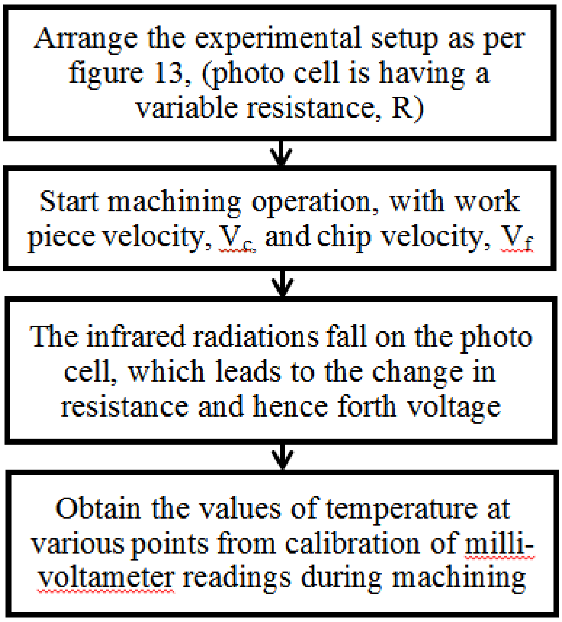

Figure 14. Process Flow Chart for IR Technique Using PbS Photocell

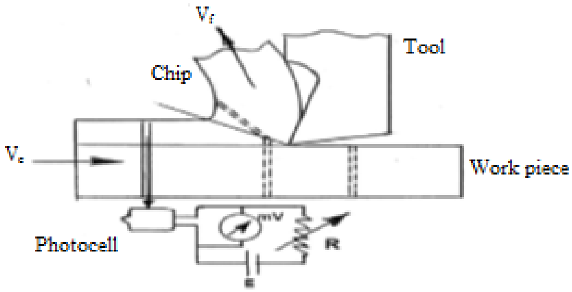

Figure 13. Experimental setup for IR pyrometers [60]

2.4. Optical Infrared Radiation Pyrometer Technique

This method is similar to IR pyrometer technique explained in (2.3), with the difference of an optical mechanism. The optical mechanism collects radiation instead to direct impingement of radiations to PbS cell, thus producing better results and reducing the exposure time. This technique is also implemented with the use of tool inserts. Major work on the technique is tabulated in Table 4.

Table 4: Summary of major works on optical infrared radiation pyrometer technique

S.No.	Scientist	Region of interest	Observation
1	Lenz [35-37]	Chip tool interface	The temperature distribution on the tool face
2	Friedman and Lenz [38]	Upper surface of chip	1.Temperature increases almost linearly with the distance from the origin of the chip formation 2. Temperature increases with decrease in feed, 3. Temperature decreases with increase in cutting speed, 4. Variation of temperature with width is small except towards the edges, 5. Influence of tool material was negligible
3	Prins [39]	--	Studied the influence of tool wear, tool geometry, feed, and cutting speed on the temperature distribution. The study is concluded on the followings: 1.The maximum tool temperature increases with increase in speed and feed, 2. A larger corner radius can reduce the temperature of the tool tip, 3. A larger included angle and a smaller cutting edge angle reduces the temperature of the tool tip
4	Ueda et al. [40]	Abrasive Grains on wheel surface	Found the mean temperature (as 820°C) for abrasive particles of Al_2O_3, A36K7VC Grinding wheel for grinding of AISI 1055 Steel, 200VHN at wheel speed of 28.85 m/s, and work speed of 0.167 m/s with down feed of 20micro meter.
5	Ueda et al. [41]	Ground Surface of Work Piece	Observed the temperature variation with the depth below the ground surface, for Si3N4, SiC, and Al2O3 respectively using diamond grinding wheel. Highest temperature was obtained with Si3N4 work material whose grinding power was largest. The mean value was estimated to be 800^0C
6	Ueda et al. [42]		1.Observed the temperature distribution of Al_2O_3, CBN and diamond during machining and predicted that temperature variation in direct proportion to thermal conductivity 2.Showed that the maximum temperature of the abrasive grains at the cutting point was found to reach close to the melting temperature of the work material
7	Ueda et al. [43]	Rake face	The temperature of a diamond tool increased with increase in the cutting speed and reached a maximum value of 190^0C
8	Parker and Marshall [44]	Rail Road wheels and brake blocks	Maximum temperature of 800^0C was recorded

2.5. Infrared Photographic Technique

Boothroyd [78; 79] developed this technique to measure the temperature distribution in the shear zone and at the chip–tool interface during machining. The experimental setup and process are given in the Figure 15 and Figure 16, respectively. This technique is widely used in case of the use of tool inserts.

Major advantages of the technique are: (i) the distribution of temperature can be analyzed over a wider region due to formation of visual image; (ii) the measurements can be taken in hazardous environment; (iii) a non-destructive method to analyze variation of temperature; (iv) very fast response and exposure time; (v) measurement without inter-reaction, i.e., no influence on the measuring objects; (vi) long lasting measurement; and (vii) no mechanical wear.

Limitations of this technique include the followings: (i) the camera requires an exposure of 10-15 seconds to record the data of the tool/work piece; (ii) preheating of the work piece is necessary so that it could be sensed by the photographic film; (iii) the camera is costly; (iv) emissivity of work piece is never the same at all points and keeps changing during the operation, which affects the quality of the picture; and (v) ability to detect the surface temperature only.

Jeelani [80] modified the technique by constructing a special light-tight enclosure around the lathe to eliminate the exposure of any outside light, and measure the temperature distribution in the machining of annealed 18% Ni Maraging steel in the cutting speed range of 0.406–0.813 m/s. The results obtained were better than those of Boothroyd [79]. The modification eliminates the need to preheat the work piece.

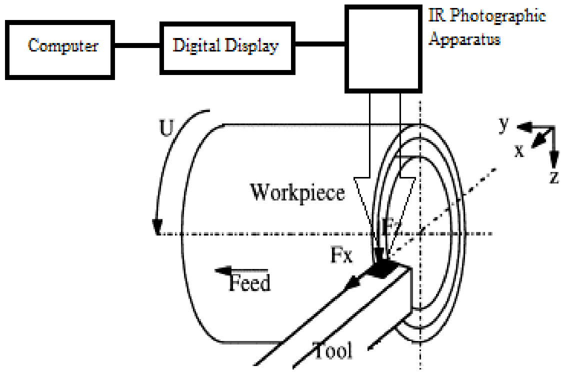

Figure 15. Experimental setup for infrared photographic technique

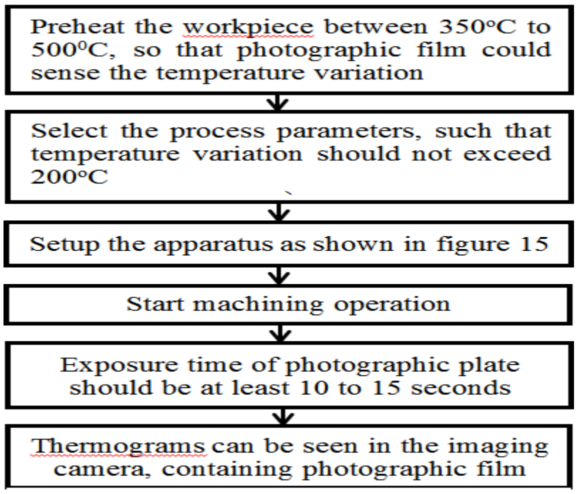

Figure 16. Process flow chart for infrared photographic technique

2.6. Fine Powder Technique

Kato *et al.* developed the technique [81] to determine the temperature distribution at various points on the surface of the tool using fine powder(s) of constant melting point. Experimental setup and process are briefly described in Figure 17 and Figure 18, respectively.

The melting points of commonly used powders in the technique are listed in Table 5. For proper adhesion of powder on the tool, aqueous solution of sodium silicate may be used. There is no need of calibration since all the used powders are having constant melting points.

Kato *et al*. [81] used NaCl, $PbCl_2$, and KNO_3 powders (10–20 μm) to determine the temperature distribution on carbide (P20), cermet, and ceramics tool (0^0 rake angle and 5^0 clearance angle) while machining AISI 1025 steel at cutting speeds 1.167 m/s and 2.5 m/s, and obtained micrographs of the sandwich surface of the tool for both the cutting speeds. From these graphs, the temperature distribution contours, along the rake face (*x*-direction) and the clearance face (*z*-direction) for carbide, cermet, and ceramic tools (Figures 19, 20 and 21, respectively) by superimposing the isothermal lines, were obtained.

Table 5. Melting point of commonly used powders [81]

Chemical Composition	**Melting Point (^{0} C)**
NaCl	800
KCl	776
CdCl	568
$PbCl_2$	501
AgCl	455
Zn	419
KNO_3	339
Pb	327.4
$SnCl_2$	246.8
Sn	231.9

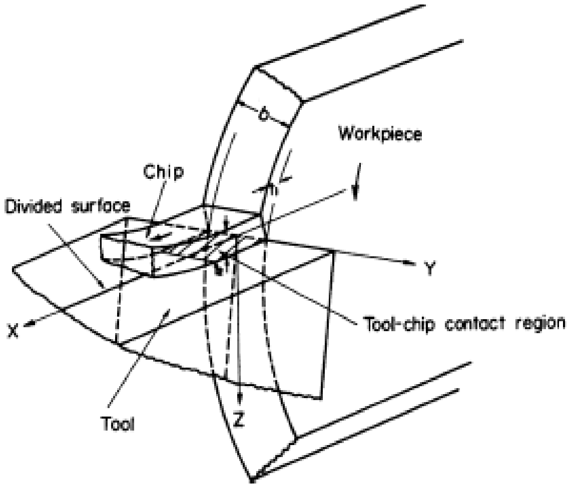

Figure 17. Schematic of the experimental method used for determining the temperature distribution in the tool using fine powder technique [81]

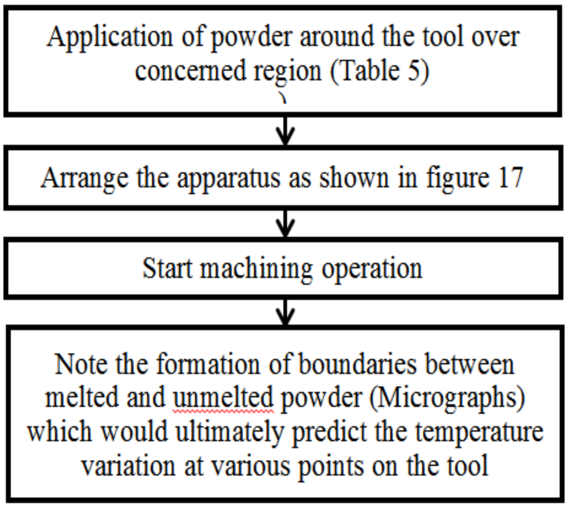

Figure 18. Process flow chart for fine powder technique

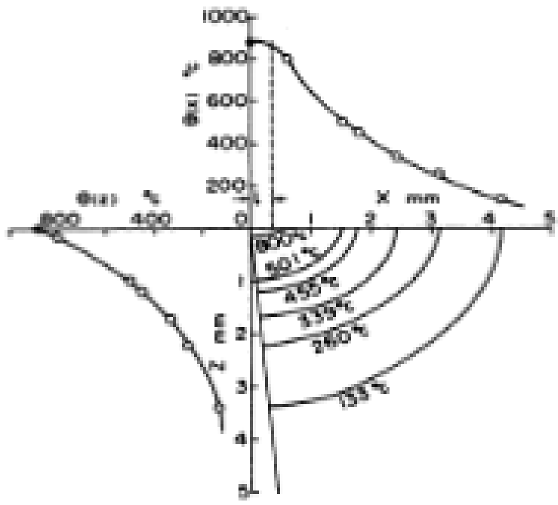

Figure 19. Temperature distribution contours along the rake face (*x*-direction) and the clearance face (*z*-direction) for carbide tool [81]

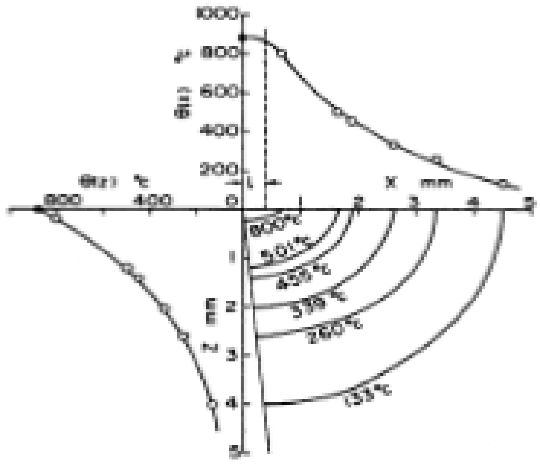

Figure. 20. Temperature distribution contours along the rake face (x-direction) and the clearance face (z-direction) for cermet tool [81]

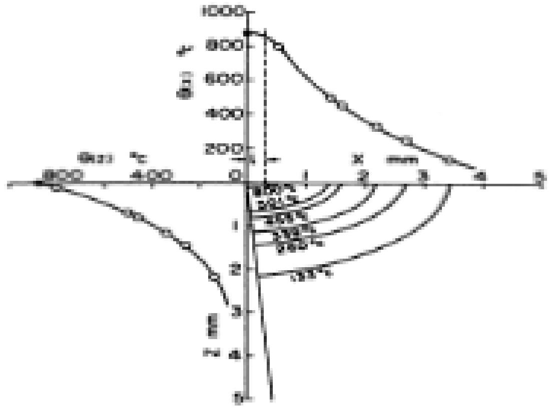

Figure 21. Temperature distribution contours along the rake face (*x*-direction) and the clearance face (*z*-direction) for ceramic tool [81]

2.7. Metallographic Methods

Wright and Trent [82] developed the technique for determining the temperature distribution at rake face of high speed steel (HSS) cutting tools. By observing the changes in microstructure of tool or by measuring the change in hardness of the tool, the temperature can be predicated. The results and charts obtained by Wright and Trent are explained in [82].

The major problems encountered in this method are: (i) it can only be used for HSS tool since it is difficult to study the microstructure change in other tools (carbide or ceramic); (ii) cutting is done at higher speeds, which results in rapid tool breakage; and (iii) microstructure change does not depend only on temperature variation and time of heating but also on other parameters like cooling period, etc. To overcome the problem, calibrations are required.

In spite of all these disadvantages, the method is capable of recording temperature in the range of 650–900^{0}C with an accuracy of ±25^{0}C.

3. Concluding Remarks

Having reviewed all the experimental techniques together, it has become clear that no technique is perfect and produces accurate results in all situations. Some methods are very complex, out of them only few produce good results; but such methods tend to be expensive. Some are very simple and economical but not very accurate. No particular technique can be applied in all situations. In conclusion, a comparative study of the merits and the demerits of all the technique, shown in Table 6, will be appropriate. Further, it is evident that a perfect technique, which is economical and implementable to all materials in all conditions, has not been yet developed.

Table 6. Comparative study of merits and demerits of various techniques

S.No.	Technique		Major Merits	Major Demerits	Remarks (if any)
1	Thermal paint		Simplest and economical	Not very accurate and prone to errors	Result verification by any other accurate enough technique is recommended
2	Thermocouple	Tool-work	Ease of experimental setup	For making observation at different point, setup is required to rearranged after stopping the machining	1. Calibration of tool-work piece pair is difficult 2. Limited transient response time
		Transverse	Capable of notifying temperature at various points without changing setup	Cannot be used for processes like grinding, drilling, milling, etc.	
		Embedded	Can be used for processes like grinding, drilling, milling, etc.	1.Temperature of surface cannot be measured directly 2. Destructive technique	
3	Pyrometer	Infrared radiation Optical Infrared radiation	1. Faster results 2. Can be used for any surface	1. Emissivity of body (under consideration) keeps on changing and hence affects the results 2. The complete isotherms cannot be plotted for every machining material	1. Photo cell is sensitive to change in ambient temperature, and IR 2.Destructive technique
4	Infrared photographic		1. Very fast response 2. Can be used in hazardous conditions	1. Requires preheating 2. Very expensive	Readings can be taken directly and long lasting
5	Fine powder		Economic	Not reliable , results are obtained in approximate temperature range	No need for calibration
6	Metallographic		Accuracy $\pm 25^0$C in the range of 650^0C to 900^0C	1.Can be used only for specific materials only (HSS) 2. High cutting speed 3. Rapid tool breakage	Requires calibration

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