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Cutting temperature: prediction and measurement methods—a review

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Abstract

The power consumed in metal cutting is largely converted into heat. Several attempts have been made to predict the temperatures involved in the process as a function of many parameters, as well as many experimental methods to measure temperature directly. Some simple analytical models can be used to show the effects of cutting parameters, such as cutting speed and feed rate. There is no precise experimental method that can be used to check the analytical results. This paper presents a review of the analytical and experimental methods used to measure cutting temperature. Some experimental results using different methods are presented. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: metal cutting; machining temperature; manufacture

1. Introduction

Machining is probably the most widely used process of manufacturing, and metals and alloys form the bulk of the materials used in this process. Therefore, the subject of metal cutting has been the focus of many researchers and has produced many publications. Since man started to machine these materials, many problems have arisen and many solutions and ideas have been proposed. Great progress has been achieved in increasing the metal removal rate and reducing the costs.

Increasing the metal removal rate means that more material can be cut in a shorter time and this has been achieved by increasing the cutting speed, the feed rate and the depth of cut. To do this in an economical way depends on many areas related with metal cutting, namely the machine tool, the cutting tool, the cutting fluid and the materials.

With respect to machine tools, it is necessary to increase power and accuracy. At the same time, they are developed in such way as to facilitate their operation, change of cutting conditions, and change of cutting tool and workpiece. Some cutting tool materials that are brittle, such as ceramics, need to be used on rigid machines.

The increase in power to remove more material in a shorter time increases the heat generation near the cutting edge of the tool, and the power consumed in metal cutting is largely converted into heat [1,2]. This heat is dissipated by the four systems processing the material: the cutting tool, the workpiece, the chip formed and the cutting fluid.

This means that the cutting tool needs to support higher temperatures at acceptable wear rates. Normally, the temperature achieved by the cutting tool is the factor that limits the rate of machining. This task forced the development of new materials for cutting tools that can resist high temperatures. Moreover, in some operations that have an interrupted cut, such as in milling, the tool has to resist a thermal cycle and mechanical shock and needs to have good toughness to support high cutting speeds.

The cutting fluids used with some cutting operations play a very important role and many operations cannot be carried out efficiently without a fluid. Among their functions [3], cutting fluids are used to cool the tool, workpiece and machine tool. They may act as a lubricant at the interface of the tool and the chip [4], depending on the conditions. At high cutting speeds, it

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is unlikely that the fluid reaches this interface and some different form of application has been experimented with [5], as well as the use of other methods of lubrication, e.g. using gases [6]. If the fluid acts as a coolant, it will remove heat from the cutting zone, whereas if it fluid acts as a lubricant, it will decrease the amount of work performed and thus the heat generation. Both ways of acting serve to reduce the temperature.

The development of new materials and alloys forced the development of new cutting tool materials. Moreover, in respect of the work material, much has been done to decrease the wear rate of tools through alloying with certain materials. These materials behave like a solid lubricant at the interface between the tool and the chip, decreasing the stress and heat generation, and the cutting force, thus decreasing the work done [7]. Sulphur and lead are the main materials used to alloy steel, which additions also promote other advantages, such as more easily handled chips, for example.

The influence on tool life of cutting temperature has been the subject of the major part of the work carried out on metal cutting, but the heat generated may also affect the surface integrity of the workpiece, for example. These effects may be more important than the tool life [8,9].

As temperature is of fundamental importance in metal cutting operations, many attempts have been made to predict it. Some works simply use a relationship between the work done and the volume of metal involved in the process to obtain an average temperature. Others use computers to help to give the distribution of temperature. The methods used to measure temperature in metal cutting have not been improved so much, so that it is difficult to prove the theoretical results in a precise manner.

In this work, a qualitative comparison is made between some experimental results obtained by several methods available in the vast literature relating to this subject and some results obtained when a theoretical method is applied.

Good agreement is obtained between experimental and theoretical results for some conditions, at least for those regions where it is possible to use an experimental technique. The behaviour of the material that is being cut and its properties are the main factors responsible for possible errors in theoretical predictions.

The next sections of this work will present what is known about heat generation during cutting, the experimental methods used to measure temperature in cutting and the analytical theories used to calculate the temperature and the gradient of the temperature. Some practical results are presented to show how temperature is affected by the cutting conditions and comparison is made with theoretical results.

2. Heat generation in metal cutting

Nearly all the work which takes place in the process of metal cutting is converted into heat. This is because there is friction to be overcome. In a simple manner, the total work carried out can be divided into three quantities: (i) work to shear the material to form the chip and the new surface; (ii) work to move the chip over the rake surface of the tool; and (iii) the work necessary to move the freshly-cut surface over the flank face of the tool. The work to shear the material to form the chip involves the dissipation of heat resulting from internal friction, while the other two are necessary to overcome the friction between the tool and chip or workpiece, which may involve internal friction because of seizure between the surfaces.

The work done will depend on the material being cut. Ductility, hardness, work hardening and thermal properties all have definite effects on the tool forces, as well as affecting the temperature. These properties, in addition to the tool material characteristics, cutting conditions and geometry of the process, will define the power and therefore, the heat generation.

In early works concerning the relationship between the chip geometry, the power consumption and the cutting parameters [10–13], the formation of chips was considered as being shearing on a simple and well defined plane, and the generation of heat on the rake face was treated on the basis of classical friction theory. The work done on the flank face of the tool was taken into account only if there was flank wear. The results are a good indication of the influence of some parameters, such as the rake angle and the cutting speed. However, the shearing action cannot be treated as a simple plane. Likewise, what happens on the rake surface of the tool is complex and cannot be treated as classical friction because of the high stress acting on the tool surface [14,15].

As has been shown [16–18], the heat generated at the tool–work interface is of major importance in relation to the tool performance, and is particularly significant in limiting the rates of metal removal. Along the greater part of the contact between the chip and the tool, there is a seizure zone where these two materials are in close contact. There is no relative movement between the chip and the tool at the surface of the tool and, depending on the cutting speed, a flow zone in the chip with great strains and strain rates or a built-up edge (for low cutting speed) is established.

Contact between the work material and the flank face of the tool will occur even for a tool without wear, and may contribute to an increase in the work temperature. The movement of the freshly-cut surface over the flank face of the tool may be treated in the same manner, depending on the cutting conditions and the tool wear rate. In this case the contact length is shorter.

When a built-up edge is formed, the heat generation due to the movement of the chip is a short distance above the flank face. The size and stability of the built-up edge is controlled by the temperature on the chip–tool interface [2]. In this case, the main consequence is the poor surface finish obtained on the workpiece, which is a factor to be observed in addition to the tool wear mechanism. A schematic diagram of a single-point cutting operation without a built-up edge is shown in Fig. 1.

Using cine-photography to observe the cutting process, Palmer and Oxley [19] found that when mild steel was machined at low speeds, the primary deformation zone had the form shown in Fig. 1. In the work of Trent [4], there is evidence of zone (iii), but not as a prolongation of zone (i).

Heat is dissipated by the cutting tool, the chip formed, the cutting fluid and the workpiece. Therefore, it is evident that the tool is heated as well the workpiece, and this is fundamental to the process. The greater part of the heat is due to work done in chip formation, with most of this heat passing into the chip, while a proportion is conducted into the work material. This proportion may be higher for low rates of metal removal and small shear zone angles, but for high rates of metal removal this proportion is small.

Boothroyd [20] proposed a method for calculating the approximate mean temperature rise in the body of the chip from the measurement of tool forces, knowledge of the cutting parameters and data for the thermal properties of the work material. Again, it is assumed that the shear zone (i) is a plane and that the chip temperature is independent of the work done in (ii). According to this, the cutting speed does not have a great effect on chip temperature. This may suggest that there is not an increase in the heat in this zone, or that the chip lost heat to the workpiece or tool.

It is unlikely that heat is lost by the chip to the tool, because the temperatures in the tool are higher than those in the body of the chip. This is why the tool–work interface is more important in respect to the metal removal rate. Most of the heat generated in this region travels into the tool and chip and as the tool is stationary, its temperature is higher. A cutting fluid used in this case will show little or no effect on tool temperature.

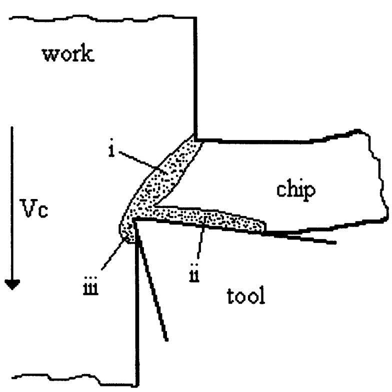

Fig. 1. Heat generation zones in orthogonal cutting.

The heat generated at the tool–work interface will also be lost to the tool holder, which can affect the dimensional accuracy of the workpiece. Depending on the temperatures achieved and the material of the tool holder, there can be dilation inf the order of 30 μm [21], thus affecting the accuracy of the operation. In this case, cutting fluid is effective.

The increase in the temperature of the workpiece is due to the work done in zones (i) and (iii) in Fig. 1. These temperatures may affect the dimensional accuracy of the workpiece, because the thermal deformation may cause positional errors between the cutting tool and the surface [22,23].

The heat generation during interrupted cutting is an important parameter for tool life control. The heat is generated in the same manner, but the changes in the temperature are cyclical, increasing during the active time and decreasing during the inactive time [24–27]. This fluctuation causes thermal fatigue of the cutting tool and the impact of the tool contributes to increasing the possibility of failure [28,29].

3. Temperature measurement in metal cutting

The difficulties in calculating the temperatures and gradients of temperatures in the cutting zone, even for simple conditions, emphasise the practical methods for measuring temperatures.

In order to evaluate the temperatures arising in the cutting zones, several techniques have been developed over the past 70 years [30]. Most of these techniques are used to measure the temperature of the cutting tool. The most extensively used method is the tool–work thermocouple [2,31]. This method is useful in showing the effect of cutting conditions, such as cutting speed and feed rate, but the absolute values are inaccurate. In this method, the thermo-electric emf generated between the tool and the workpiece during cutting is measured. The cutting zone forms the hot junction, while an electrical connection to a cold part of the tool and the workpiece forms the cold junction. The tool and workpiece need to be electrically insulated from the machine tool. The difficulty of this method is concerned with the necessity for an accurate calibration of the tool and workpiece materials as a thermocouple pair [32,33].

A temperature gradient exists along the contact of the tool with the chip and it is uncertain whether the thermocouple is measuring the lowest temperature at this interface, or a mean value. Accordingly [34], the quantity measured in the tool–work thermocouple method is the average thermo-electric emf at the interface between the tool and the workpiece. In general, this emf does not correspond to the average interfacial temperature, this being the case only if the temperature is uniform or if the thermo-electric emf of the tool–work material combination varies linearly with temperature.

Another method used to measure the temperature and gradients in the tool is that of inserted thermocouples [35]. Using thermocouples of small diameter, it is possible to obtain good results in relation to the temperature gradients in the tool by means of many small holes in different positions. The disadvantage here is that it is impossible to put thermocouples very near the cutting edge where there are high temperature gradients.

With most tool materials, such as ceramics used in high-speed cutting, the brittleness and electrical resistance are significant and make it difficult to implement a contact-type sensor such as that described above [36].

A very interesting method was developed to measure the temperature in the flank face of the tool using wire of a material different from that of the workpiece and the tool [37]. This wire is inserted into the workpiece into a hole of a small diameter and is insulated. When the material is been cut, this wire will also be machined, and when this happens a thermocouple is formed between the wire and the tool. With regard to the results obtained, the temperature of the tool flank face is affected little by the cutting speed, feed rate and depth of cut. For carbon steel, for example, the temperature obtained was about 400°C, independent of the tool material. The temperatures obtained by this method are lower than when using the tool–work thermocouple method. The errors in this method arise from the uncertainty as to what happens in the cutting zone when it is touched by the thermocouple. Moreover, the duration of the contact is very short.

A method was developed by Kato et al. [38] to measure tool temperature distribution within the tool by means of fine powers that have a constant melting point. The tool was divided into two symmetrical parts parallel to the chip flow direction and fine powders were scattered on one side of the divided surfaces. The tools were then put together and used to cut. The temperature distribution is obtained using different powders and observations of the extent of the melted areas. Some results using this method show that the temperature tends to be absorbed gradually at a point away from the cutting edge, but very rapidly at the cutting edge, the time required being about 1–2 min. The temperature gradient obtained was little different from that obtained using other methods.

The temperature distribution in the tool may be obtained by using information about the changes in the hardness and microstructure of the steel tool [39]. It is necessary to calibrate the hardness of the tool against the temperature and time of heating, and samples of structural changes at corresponding temperatures. These methods permit measurement of temperatures to an accuracy of ± 25°C within the heat-affected region. However, these methods are arduous and difficult to use [40].

The technique of measuring temperature by the measurement of radiation is sometimes very useful in obtaining the surface temperature of the workpiece, the chip and the tool [41–46]. This method gives information only about the temperature on exposed surfaces, although some experimental techniques attempted to measure the temperature distribution on the flank or the rake face of the tool through small holes in the workpiece [47,48]. However, these holes change the process to interrupted cutting, and it is doubtful if the temperature measured is the same as that for non-interrupted cutting.

The radiation methods are very complicated and suitable only for laboratory studies. Extreme care is required in assembling and using the radiation pyrometer [49] and the minimum temperature detectable is a limiting factor for the use of these set-ups. Today there are more simple infrared sensors with quick responses and there are no minimum temperatures for application in metal cutting.

A recent application to use an infrared sensor to measure the temperature of the machined surface during cutting has been published [50]. Basically the method consists of measuring the temperature on the machined surface just below the cutting edge. The temperature is measured at 3, 6 and 9 mm below the cutting and then the results are used to extrapolate to the cutting edge. The method, first developed for dry conditions, is modified to be used when cutting fluid is applied. Some results using such methods are presented in Section 5.

Another method involving the use of thermo-sensitive paints gives results, but they are not considered to be accurate [42].

4. Analytical models of temperature distribution

There are many analytical treatments [2,51–53], the finite-element method [36,54–61] and the boundary-element method [62], of heat conduction with moving or stationary heat sources, together with the kinematics, geometry and energetic aspects of the metal cutting process.

In the analytical models, it is often assumed that the chip is formed instantaneously by a shearing action in a plane (shear zone). In addition, the chip–tool interface is assumed to be a uniform plane with the heat generated being due to friction between the two surfaces. The analyses of Loewen and Shaw [51] assumes that shear and frictional energy is distributed uniformly, and that there is no redistribution of the thermal shear energy going to the chip during the very short time that the chip is in contact with the tool. The relative importance of the several variables influencing tool face temperatures is discussed. The results explained the high temperatures that are observed in the machining of titanium alloys.

In the work by Stephenson [52], relaxation methods are applied to the workpiece and shear-plane temperature problem, and were able to solve numerically the equation for heat transfer in a material moving in a direction perpendicular to a stationary heat source. The complete temperature distribution in the workpiece and chip was obtained. Lo Casto et al. [53]assumed that the heat transferred by conduction in the direction of motion of the workpiece or chip may be neglected, thus solving the same equation. The finite-element analyses of Lo Casto et al. [53] accounts for the primary and secondary zones being finite in size, and obtained temperatures for the workpiece lower than those found by Stephenson [52].

Using finite-element analyses, Muraka et al. [56] investigated the influence of several process variables on the temperature distributions on the tool flank face and rake face. The rate generation was calculated using some experimental methods to measure strain in the primary and secondary deformation zones. An empirical expression was used to relate the flow stress of the material being cut and the strain, strain rate and temperature; errors may arise in the results due to this measurement and estimating. The results obtained are very interesting, and show the effects of the main variables. For example, the highest temperature along the tool flank, similar to that along the tool face, occurs at some distance from the cutting edge and increases with cutting speed and feed rate. According to Chan and Chandra [63], the calculation of thermal energy from frictional resistance is affected by a number of factors. Material properties are constantly changing and difficulties also arise when attempting to quantify the real area of contact.

Simon [6] analysed the dependency of the thermal failure of a cutting tool on a temperature gradient. It is suggested that by cooling the lower face of the tool it is possible to increase the temperature gradient of the cutting surface, thus decreasing the wear level of the tool. The effect of the contact between the tool and the workpiece is considered only if there is flank wear.

All of these works are very fundamental and use powerful tools. The results give an excellent idea of the influence and importance of the parameters involved in the process. It is difficult, however, to confirm these models by experimental methods.

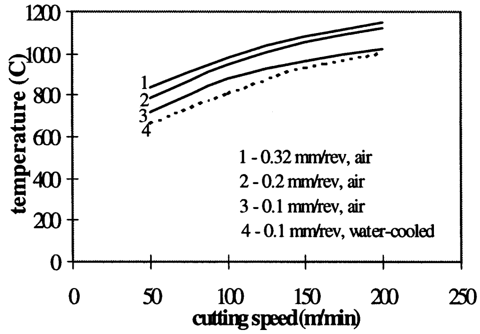

Fig. 2. Effect of cutting speed, feed and cutting fluid on temperature [64].

5. Temperature and cutting conditions

The major part of the work regarding temperature in metal cutting has been focused on the tool temperature and on analytical models, this being due to the wear of tools having been the concern of many researchers; wear is sensitive to the temperature in the cutting zone.

The temperature in the cutting zone will be affected by the cutting conditions: the cutting speed, the feed rate, the depth of cut and the tool geometry. It will also depend on the properties of the workpiece material, as well as on the physical properties of the tool. There are numerous results in the literature, both analytical and experimental, regarding the influence of the cutting conditions on the temperature of the tool, the workpiece or the chip. The temperature increases because more heat is being generated and/or is concentrated in a small area an/or less heat is being dissipated. According to this the effect of the cutting conditions (cutting speed, feed rate and depth of cut) will be to increase the temperature. Less obvious effects are those of the tool geometry, the material (workpiece, tool) and the cutting fluid.

Using the tool–work thermocouple method, results were obtained [64] (shown in Fig. 2) for a low-alloy engineering steel machined with cemented carbide tools. Temperature was measured as a function of cutting speed for three different feed rates and compared with the results for dry cutting and cutting using water as the cutting fluid. The results give a good idea about the values of temperature achieved by the tool, as well as the effect of some cutting conditions. The water used acts as a coolant and its effect decrease as the cutting speed increases. As the temperature affects the properties of the material, the latter becomes easily deformed at higher temperatures. When cutting fluid is used, it changes the properties of the material in the same manner. It seems that an equilibrium is achieved between the effect of the cutting fluid and the heat generation for these cutting conditions.

The same trend can be obtained using a simple analytical method to determine the approximate temperature at the chip–tool interface [51]. The heat in this region came from the work performed to move the chip over the flank face, so there is a contribution from seizure zones and sliding zones. Errors will arise from the fact that it is impossible to distinguish between these two regions and the need to measure the strain in the seizure zone. The method used to obtain the sample to measure these strain is the quick-stop method, which consists of a device to disengage the tool very quickly while it is cutting. This enables the freezing of the cutting zone, but some damage is done. Both experimental and analytical methods are affected by the presence of a built-up edge.

Some works usied metallographic techniques and changes in the hardness of the tool to show the distribution of temperature in the tool. According to these results, the maximum temperature on the rake face on the tool is remote from the cutting edge. An example is shown in Fig. 3. In Usui et al. [65], the same model of temperature distribution was obtained, i.e. higher temperatures on the rake face of the tool are remote from the cutting edge.

A similar distribution is obtained when finite-element models are applied. The maximum temperature is at some distance from the cutting edge and a good agreement is obtained with the experimental results [57]. The difference in terms of distribution patterns is at the region near the cutting edge, where the calculation gives lower values for temperatures.

These distributions of temperature have been explained in terms of the seizure zone of the cutting tool interface. According to [4], the formation of a crater on the rake face of the tool will start in the region of higher temperature. This happens for many materials and cutting conditions, although for some materials there is a great difference from the above model. Fig. 4 shows the results using the same method for high-conductivity copper.

The results can be explained by the ductility of the copper being high and the seizure zone, if formed, extending from the cutting edge of the tool. Generally, the results have shown that for a fixed combination of tool and workpiece, the tool temperature will be affected by the extent of the contact length between the chip and the tool. The temperature will increase with the contact length. Consequently, the parameters that affect this zone will affect the temperature [42]. A lubricant, for example, will affect the temperature at the interface if it decreases the seizure zone.

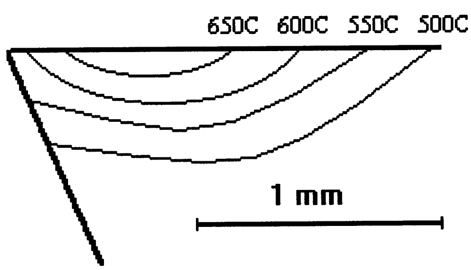

Fig. 3. Distribution of temperature on the rake face of a tool [4].

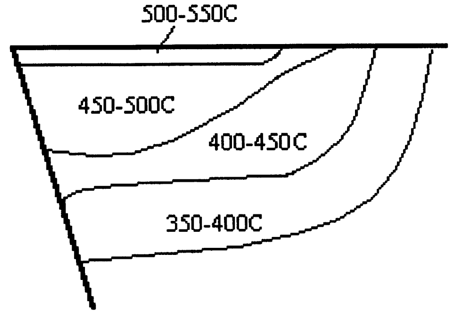

Fig. 4. Distribution of temperature on the rake face of the tool when cutting high-conductivity copper [4].

Fig. 5 represents the results obtained by Machado et al. [66], where the effect of the contact length between the chip and the tool was studied for the orthogonal cutting of aluminium. The cutting conditions were maintained constants (cutting speed 120 m min^{-1}, depth of cut 1.59 mm) and the different contacts lengths were obtained by means of restriction of the flank face of the tool. These results can be compared with the effect of seizure-zone size, which means that if a lubricant is achieved in the tool–chip interface, the effect will be a drop in the heat generation and a decrease in temperature.

Using the infrared sensor mentioned in Section 3, the temperature on the machined surface for the dry cutting of an AISI1040 steel was measured; the results are presented in Fig. 6. To obtain the temperature close to the cutting edge by extrapolation, measurement at at least three different positions is needed. Fig. 6(a) shows the variation in temperature after the start of the cutting for 3 mm below the cutting edge using $V_c = 40$ m min^{-1}, $f = 0.15$ mm rev^{-1} and depth of cut = 2 mm.

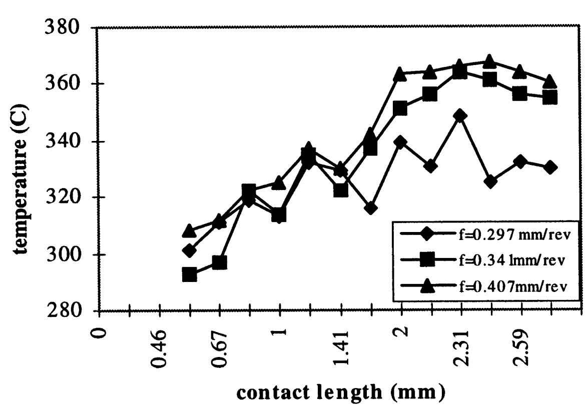

Fig. 5. Temperature for different contact lengths and feed rates [66].

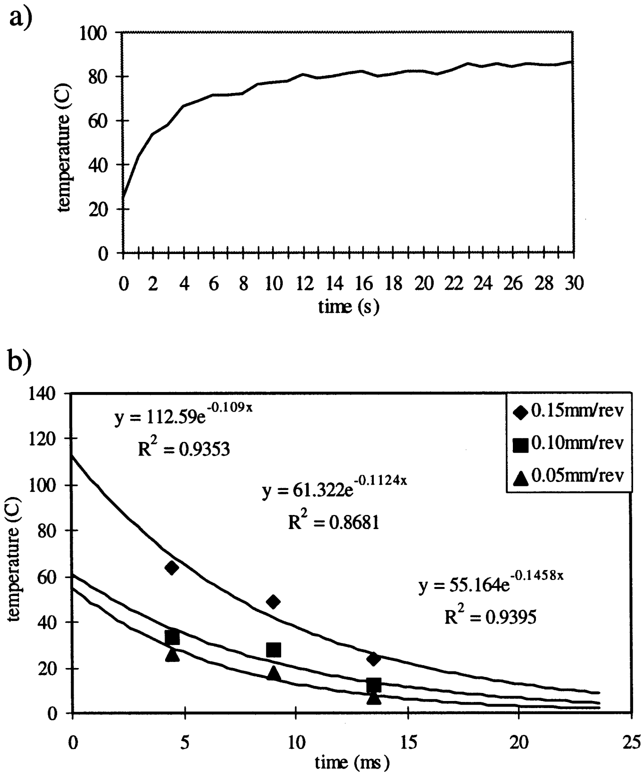

Fig. 6. Temperature on the surface of AISI1040 steel machined at 40 m min^{-1} and three different feed rates: (a) temperature during cutting at 0.15 mm rev^{-1} and 3 mm below the cutting edge; (b) extrapolation of the results [50].

According to the graph, the temperature stabilised about 30 s after the start of the cut. During the test, the temperatures were recorded each second, the final temperature being 89°C in this case. For the same conditions at 6 and 9 mm, the temperature was 68° and 53°C, respectively. Using these values, the temperature close to the cutting edge was extrapolated and the final result was 113°C. Fig. 6(b) shows the extrapolation curves for three feed rates, 0.15, 0.1 and 0.05 mm rev^{-1}. Using the measurements of temperature at the three different position, it is possible to calculate the average cooling rate of the workpiece. In this case, it will be: 4667°, 2222° and 2889°C s^{-1} for 0.15, 0.1 and 0.05 mm rev^{-1}, respectively.

6. Conclusions

The main signals that can be measured in a metal cutting operation are force, surface roughness, chip dimensions, strain, tool wear and temperature. Among these, the temperature is the most difficult to measure, which explains the numbers of different methods used over the years.

The majority of methods used to measure the temperature are concerned with the temperature at the chip–tool interface, and for this the tool–work thermocouple is the best method. It gives the aspect of the temperature trend with the cutting parameters, such as cutting speed, feed rate and depth of cut.

The infrared method gives a good indication of the maximum temperature of the workpiece as well as its cooling rate.

Through the measurement of force and strain, it is possible to estimate the work carried out during cutting. The temperatures achieved by the system can be calculated with a rough approximation, considering that this work done is converted into heat that is dissipated by the tool, the chip and the workpiece. The application of a cutting fluid to the system adds more difficulty to the problem of measuring temperature.

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