HOT MACHINING: A REVIEW

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Abstract. *One of the main goals of the metal-mechanical industries is the reduction of the production costs through the productivity increase. For this, larger rates of material removal are searched for smaller intervals of time. In this way, the increase of the tool life becomes fundamental in machining mainly of hard-to-cutting materials.*

In the attempt to reach this goals, many researchers have been used the hot machining method. This method consists, basically, in the heating of the workpiece hundreds of degrees Celsius above room temperature with aid of an external source of heat. Thus, the reduction of the shear stress of the material of the piece is gotten and, hence, is possible to obtain a smaller wear of cutting tool in relation to the conventional machining.

This paper presents a review of hot machining, where the different techniques are presented together their results. This work involves, since the heating using an electric current method between the piece and the tool in the end of the nineteen century until now a days where is used the laser as a source of heating. This latter is used mainly in modern materials of hard machining such as advanced ceramics and alloy steels.

Keywords*. hot machining, tool life, machinability*

1. Introduction

According to Mielnik (1994), the hot machining can be defined as a process of material removal, with solid cutting tool, in which the workpiece is heated up the hundreds of degrees Celsius above the room temperature for an external source of heat, so as to reduce the shear strength of high strength and difficult-to-machine materials.

This method provides, in certain conditions, reduction of stress in machine tool, increase of rate of material removal, increase of the tool life, and the control of workpiece properties and geometry, comparing these variables in relation to conventional machining with the workpiece in the room temperature. (Rozzi et all, 2000).

Mielnik (1994) describes that this definition excludes such chipless, non-cutting tool, non-contact ablation processes that removal happens without contact tool-workpiece. The high-speed machining processes are also excluded, in which the generation of heat is generalized in the workpiece. In this case, the action of the tool provides temperature elevation, and she suffers the consequence through acceleration of its wear, while in hot machining there is an external source that assists in elevation of temperature.

According to Kitagawa et all (1988) machining by softening the workpiece is a more effective way than strengthening the cutting tool.

The hot machining process is researched at a long time. Mielnik (1994) mentions that a patent of the idea of heating up the piece, before the machining, for an electric current of intensity elevated between the piece and the tool was granted to B. C. Tilghman in 1889. Another patent hot machining was emitted to M. Berliner in 1946.

Several researchers published articles of hot machining in the late 1940s and early 1950s like Krabacher & Merchant (1951). These researchers noticed in its experiments that it happened increase in the tool life when it increased the temperature of the workpiece surface. Generally, it has been observed that there is a limit to these increases and that, in fact, the tool life decreases after a certain optimum temperature (Mukherjee & Basu, 1973). The Figure (1) demonstrates the relationship between the tool life and the temperature in the workpiece. Krabacher & Merchant (1951) justified that beyond of the optimum temperature the tool material become softened and easier to wear out. While Shaw (1951) attributed the decrease of tool life that besides the shear strength, however, another factor play an important role, and that is the work material's tendency to strain-harden. It has been observed that the coefficient of strain-hardenability, as also yield point, decreases with increasing temperature.

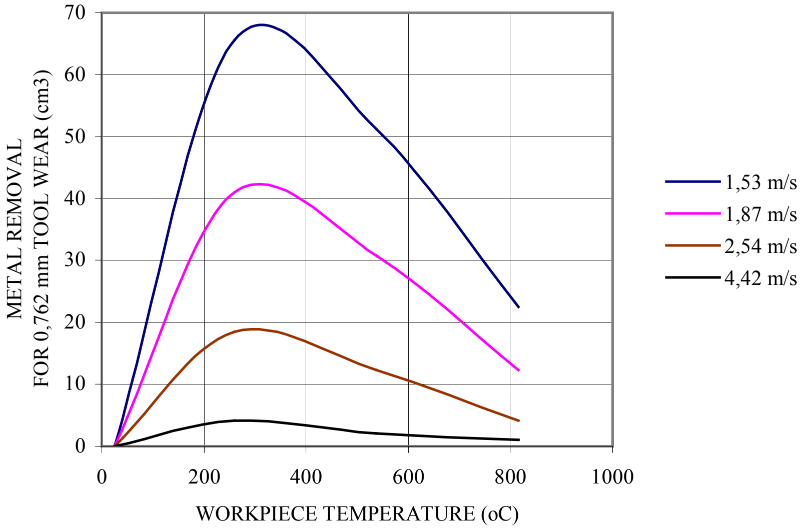


Figure 1. Relationship between tool life and workpiece temperatures (Krabacher & Merchant, 1951).

In the experiments with the hot machining process the main components are: the source used to heat up the piece, the temperature of the interface tool-workpiece and the tool machine used. The aspect that to be investigated in this study, as a decisive factor to turn the viable process economically, it is the way with that the piece is heated up, by virtue of the type of the source of heat used.

2. Types of sources of heat used for hot machining

The types of sources for heating of the pieces are:
- A furnace;
- An electric resistance;
- A flame;
- Induction;
- An electric arc;
- An electric current localized between the piece and the tool;
- A plasma arc, and;
- Laser assisted machining (LAM).

The heating with electrons beam has been proposed, but its use is not applicable due to the high cost of the equipment.

Now a days the processes commonly used are:
- Electric current between the workpiece and the tool, mainly for light or finishing cuts;
- Plasma arc, for heavy cuts, and;
- Laser assisted machining.

Barrow (1969) divides the heating techniques in two types:

- Bulk heating: in this process the whole workpiece or a considerable part of its is heated up, when it is used as source of heat a furnace, flame or resistances, for example. The main disadvantages of these techniques are: the distortions caused by the thermal dilation of the material on cooling; slow temperature rise; and danger to the operators. These techniques are relatively cheap and simple, and have been used to restricted applications in industry.

- Localized heating: the heating is concentrated immediately in the vicinity of shear zone. In this type is that they are concentrated the most recent researches, in which are included induction, laser, and carbon or plasma arc. In general, these techniques obtain better results than the bulk heating, even so, they tend be more expensive and difficult of applying in the industrial conditions.

Barrow (1969) describes that the main requirements for techniques of heating of workpieces are:
- The heating should be confined as far as possible to the shear zone;
- The application of a high density of heat is necessary so that it is obtained a high temperature in workpiece;
- The heating method should be relatively cheap to install and for to operate;
- The method should be applicable to machines of production line, and under industrial conditions, allowing fast machines set-ups;
- It is essential that the used method doesn't dangerous to the operators, and;
- The temperature should be controlled quickly and easily.

3. Hot machining process with electric current in the interface chip-tool

In his research, Barrow used the application of an electric current between the interface chip-tool to heating the workpiece, obtaining as result a significant increase of the tool life in relation to machining with the workpiece at the room temperature. The system used by Barrow consisted of a voltage source applied to a circuit composed of the workpiece and cutting tool, the contact with the workpiece is best achieved by using a spring loaded cooper-graphite brush. The cutting tool was the other electrode insulated from machine frame, as shown in Fig. (2).

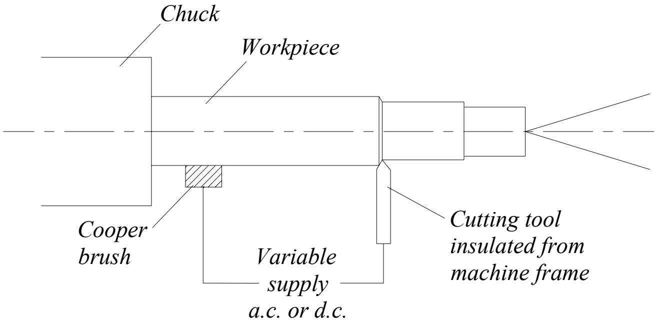


Figure 2. Circuit diagram for hot machining with electric current (Barrow, 1969).

In these works were tested AC and DC voltage sources that presented similar results, and in some cases the DC voltage presented better results under the point of view of the tool life. In the heating with AC voltage a tendency existed to the appearance of vibrations, even so in most of the cases this vibration was considered insignificant.

The advantages of the heating method for electric current between the workpiece and the tool are:

- Simplicity and adaptability to productive processes;
- The apparatus can be transferred easily for another machines, and with small alterations the same method can be used for milling processes and drilling;
- Heat is generated at or near to the shear zone;
- Very little "excess" material is heated;
- The technique is relatively cheap to install and operate;
- There is no danger, since the current is generated by source of low voltage;
- It is clean and easy to apply, and;
- Temperature control is easy and there is quick response to temperature rise.

For turning of hardened Ni-Cr and Ni-Cr-Mo steels, this method has been providing an increase of 300% at the tool life. In general, for each group workpiece-tool there is a optimum point of feed rate and cutting speed, as well as a value of electric current that provides a maximum value of tool life.

The disadvantages of this method:

- Since de heat is generated at the chip-tool interface, the rise in chip-tool interface temperature is an important factor in limiting the improvement in tool life;
- The tool tips should be made from an electrically conductive material, and;
- It cannot be used for process with high depth of cut.

When the tool is not made from electrically conductive material, such as ceramic tool, bars of graphite impregnated copper, wire brushes ,or roller electrodes can be used to establish the contact with the workpiece, and this contact should be just ahead or just back of cutting tool.

Ellis & Barrow (1971) studies this method using a carbide tool tip as an electrode and discussed the effects of hot machining on surface features and some geometrical and metallurgical features of the workpiece and the chip with a scanning electron microscope and then using conventional metallurgical techniques.

In this tests was machined a steel tube with the following specifications: 0,32% C, 0,57% Mn, 0,23% Si, 4,16% Ni, 1,19% Cr, 0,16% Mo, up to 0,05% S. This tube was 53,975 mm out diameter with 3,175 mm wall thickness. Were used current AC values of 200 A, 400 A and 600 A in circuit to heating the workpiece, the feed rate remained constant at 0,0726 mm and cutting speed was used one series at 0,305 m/s and other series at 0,508 m/s.

The researchers describes that in conventional machining a build-up edge (BUE) was presented at both 0,305 m/s and 0,508 m/s cutting speed, and the BUE was eliminated by the current heating. A smaller current was required to eliminate the BUE at higher cutting speed.

The theory suggests that in hot machining the BUE will disappear at lower value of heating current at a higher cutting speed because a higher cutting speed naturally leads to a higher cutting temperature in conventional machining. A smaller temperature increment would be required from heating source at a higher cutting speed to achieve the critical cutting temperature at which the BUE would disappear.

Bhattacharyya & Scrutton (1971) studied theorically the plastic flow of the materials at the chip-tool interface during hot machining using the method of heating with electric current between the tool and the workpiece, and they verified that all metallic materials have a optimum temperature value to machining, and this value depends of the physical properties of each material type.

Besides the influence of the temperature, Mukherjee & Basu (1973) associated the influences of the variables: cutting speed, depth of cut and feed rate, in the study of the behavior of the tool life and of the surface roughness of the workpiece. To evaluate the influences of these variables, the researchers concluded the method of analysis factorial to obtain a mathematical equation. The researchers ended that in the hot machining the temperature becomes a significant parameter, as well as the conventional parameters (cutting speed, feed rate, depth of cut, etc.).

In works of the Mukherjee & Basu (1973) they turned a workpiece of Ni-Cr steel with a tungsten carbide tipped tool, dry, and they found the equations for the tool life and surface roughness of the workpiece:

$$T = \frac{11{,}25.\theta^{0{,}06554}}{V^{0{,}08554}.f^{0{,}05918}.a_p^{\;0{,}0228}} \tag{1}$$

$$R_a{}' = \frac{10{,}22.f^{0{,}10315}.a_p^{\;0{,}02036}}{V^{0{,}0701}.\theta^{0{,}2545}} \tag{2}$$

Where:
T is the tool life, in min.;
R_a' is the surface roughness, in 10^{-1} microns;
V is the cutting speed, in m/min;
f is the feed rate, in mm/rev;
a_p is the depth of cut, in mm, and;
θ is the workpiece temperature, in °C.

In this conclusions, Mukherjee & Basu (1973) stand out that in the hot machining the heating must be localized in the region of cutting and be short duration to ensure that no structural changes occur in the body of the workpiece.

Later, Basu & Ramamurthy (1979) determined the equation of tool life machining a 1,92% C - 13% Cr steel in a optimum temperature of 400°C, as shown:

$$T = \frac{2{,}245.10^5.V^{0{,}493}}{a_p^{0{,}732}.f^{0{,}322}.HB^{2{,}21}}\ \text{min} \tag{3}$$

Where:
HB is the Brinell hardness.

Mielnik (1994), in his works presents the classes of materials that the hot machining is applied:

- Tough materials, difficult to machining, developed to support high temperatures and to resist the corrosion;
- Fragile materials, such as chilled cast irons;
- Spray or weld deposited metal coatings, and;
- Steels that absorbed in its surfaces sand or slag, which are extremely destructive to cutting tools.

4. Hot machining process using electric arc

Mielnik describes that in The University of Iowa, since the decade of 60, has been studied the hot machining, using an 800 A inert tungsten arc heating source. The material machined has been an 18-8 stainless steel, and the usual surface temperature was 816°C, and the usual depth of cut was 0,635 mm.

To compensate the temperature variations and to facilitate the rupture of the ductile chip, the lathe it was adapted to operate with constant pressure feed rate by means of a hydraulic cylinder. To facilitate chip disposal, the hydraulic cylinder reduces periodically the constant pressure feed rate momentarily to create narrowing in the thickness of chip promoting its fracture.

In these experiments several positive rake tool geometries tool were used. Lately it has been used a triangular carbide insert, set up in a water-cooled tool holder with a chip breaker.

In the researches with hot machining, in this university, new concepts were introduced:

- The application of lubricants in the hot machining;
- An initial oscillation in the heating source to increase the depth of the heating;
- Constant pressure feeding, and;
- Formation of segmented ductile chips.

5. Hot machining using oxyacetylene torch

In a research of the hot machining of a 0,86% C, 10,88% Mn austenitic manganese steel, Pal & Basu (1971) used an oxyacetylene torch positioned in front of the cutting tool for heating a workpiece in a shaper in which a vertical, single-point, tungsten carbide tool, 31TW/F, was used. The tool life equation was obtained for an average of values measured at 400°C, 500°C and 650°C.

$$T = 0{,}0636.V^{2{,}06} \text{ min} \tag{4}$$

A optimum temperature was occurred for the value of 650°C, at which the tool life begins to decrease. This phenomenon, and " break-back " point is justified with base in the type of wear of the tool that occurs, abrasive wear involving build-up edge (BUE) or adhesive wear.

6. Hot machining process with plasma arc (PEM)

A commercial process of hot machining with plasma arc was presented in 1971. Production Engineering Research Association (PEAR) in Great Britain developed this model and it was called process PERA CUTFAST.

This technique promoted a reduction of total cost of an machining process around 40% when the company Head Wrightson Company applied it in a workpiece that was an 5,50 m diameter cast steel ring weighing 22 tons, surfaced, in part, with a weld deposit of stainless steel.

This heating method consists of a torch of gas injected in a point just ahead the edge of cutting tool that is used as mean by plasma that happens in the workpiece surface. The torch is concentrated, and the arc has as negative pole the tungsten electrode and the workpiece is the positive pole. Fig. (3).

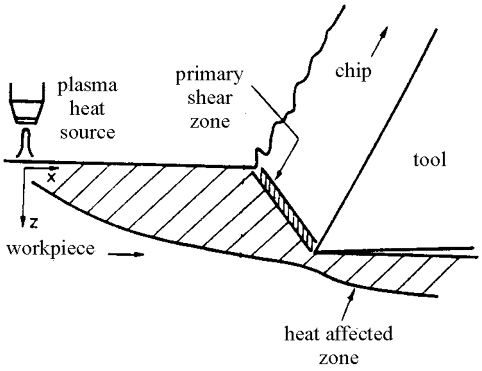


Figure 3. Heating process in plasma assisted hot machining (Hinds & Almeida, 1981).

The advantage of an external source of heat, as the plasma arc is that the heating presents a larger independence of the machining process. This method attends the characteristics described by Barrow (1969) that for the device to be ideal should present among another: the confined heating the nearest possible of shear zone, a high density of heat so that to obtain a high temperature in the piece, and an easy and fast control of the temperature.

Kitagawa & Maekawa (1990) also used as source of heat the energy produced by plasma arc, argon and hydrogen as the working gas mixture.

These researchers used in the experiments with glasses and engineering ceramics (pyrex, mullite, alumina, zirconia and silicon nitride) and a sinterized high speed steel (HSS).

The heating with plasma is investigated for besides reducing the hardness of the ceramics materials to change the characteristic of chip formation, changing from brittle fracture type to continuous form.

In the case of the nitride silicon, cutting forces markedly decreases as the workpiece was heated up the temperatures above 1.050°C.

The change of the characteristics of chip formation provides a better finished surface with a fewer defects.

In the machining of ceramics materials workpieces which has low conductivity, the nozzle was used as negative pole of the arc, as is demonstrates by Fig. (4).

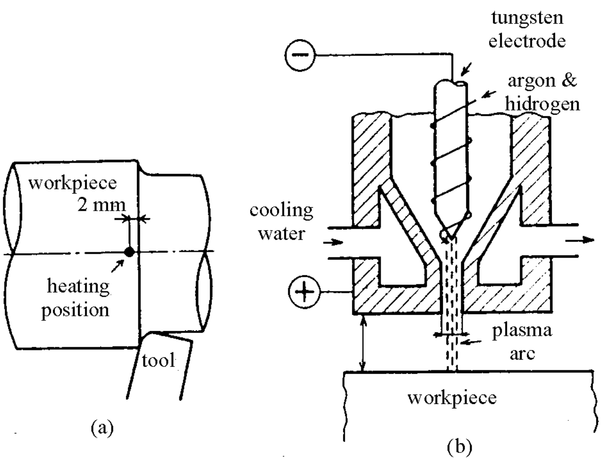


Figure 4. Set-up for plasma heating: (a) heating position; (b) plasma torch (Kitagawa & Maekawa, 1990).

The studies of cutting of ceramics materials have been developed from middles of the 70s of the academic and practical point of view, even so the hardness and to brittle of these materials difficult the machining process, restricting its applications in the manufacture of pieces.

The alternatives for manufacturing of these pieces are: grinding and polishing, even so, these processes present low rates of material removal.

Thus, the hot machining appears as a new alternative for machining of this type of materials with the advantage of increasing the removal rate significantly in relation to these processes.

An important consideration in the hot machining is the involved cost. Although high consumption of energy, Kitagawa et all (1988) observed that under certain conditions of arc current the total cost of the process is reduced above 50%, in the turning of the 3,18% C cast iron, due to the excellent economy caused by the decrease of changes of tools.

Even so, this process presents the disadvantage of to need a source of gas and of a considerable space around the tool machine for its installation.

Leshock et all (2001) studied the machining with plasma of a workpiece of Inconel 718 establishing a three-dimensional mathematical model to determine the distribution of the temperature in a cylindrical piece. The results were compared with experimental results.

Comparing the results obtained through the model and of the experiments it was noticed a good approach.

Figure (5) shows the results obtained in this study when it was compared the shear energy for three different cases: conventional machining with a carbide insert, conventional machining with WG-300 inserts (aluminum oxide reinforced with silicon carbide whiskers), and hot machining with plasma aid. The specific shear energy with a ceramic insert is much lower than the carbide case since a higher machining speed can be adopted. With a similar cutting speed, generally, the shear energy can be further reduced by plasma heating of the workpiece.

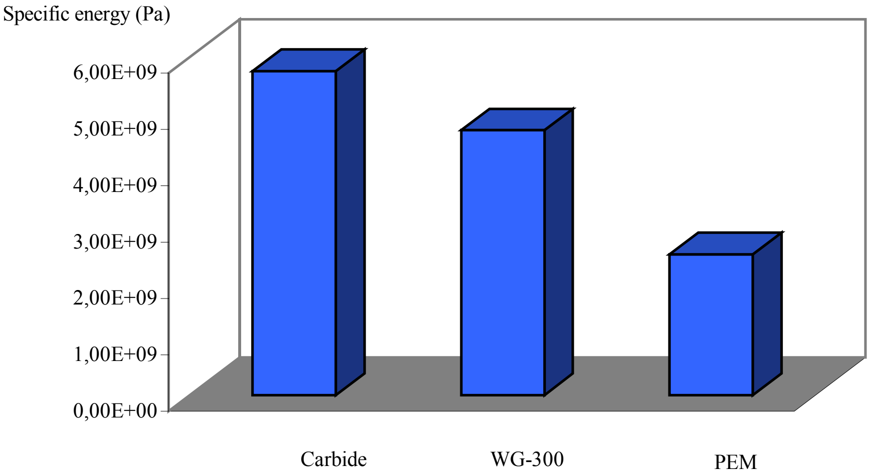


Figure 5. Comparison of specific shear energy for conventional machining with carbide and ceramics inserts, and PEM (Leshock et all, 2001).

7. Hot machining using flame

Another method of heating of the workpiece is using flame generated by the mixture of oxygen and GLP (liquefied gas of petroleum). Özler et all (2001) accomplished experiments using this device and observed the increase of the tool life when temperature was increased. In the experiments the temperature was varied up to 600°C. In the interval among the room temperature up to 200°C was observed a very large rate of increase of the tool life. Between 400°C and 600°C the values of the tool lives were roughly equal, therefore as the austenitic manganese steel has a recrystallisation temperature in the range of 500 - 650°C, the high heating temperature can have been causing undesirable structural changes in the material and an increased wearing of tool exist. Then, in the hot machining of the austenitic steel, the selection of the temperature of 400°C as temperature of heating of the workpiece can be the most appropriate, in the cost point of view and of preservation of the characteristics of the material of the workpiece.

In this study, it was observed that as the cutting speed was increased, the tool life was decreased, considering an interval between 22 m/min and 75 m/min, however, the results indicate that in relation to conventional machining, the hot machining propitiates the operation with higher cutting speeds.

Besides the influences of the described variables, it was observed in smaller proportions that when increases the feed rate or the depth of cut, the tool life decreases.

A tool life mathematical model was determined using the factorial analysis method and it was obtained the Eq. (5):

$$T = \frac{12{,}9978.V^{0{,}9632-0{,}0947.\log V-0{,}0238.\log f+0{,}0059.\log a_p}.\theta^{4{,}7687-0{,}3218.\log\theta-0{,}1853.\log V+0{,}038.\log a_p}}{f^{1{,}3062+0{,}2449.\log f-0{,}0230.\log\theta}.a_p^{0{,}1989+0{,}0907.\log a_p+0{,}0258.\log f}} \quad (5)$$

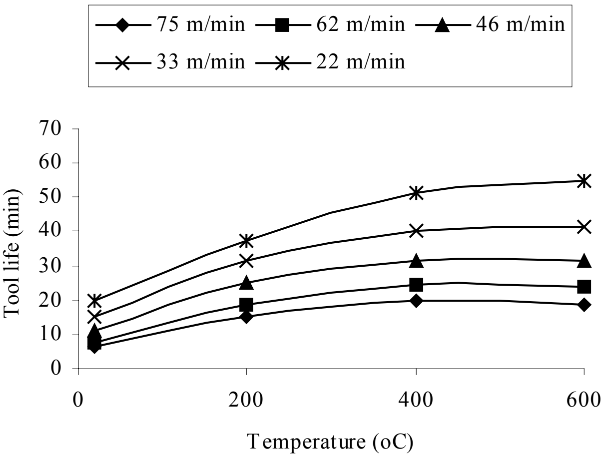


Figure 6. The relationship between cutting temperature and tool life (f = 0,2 mm/rev, a_p = 1,5 mm) (Özler et all, 2001).

Later on, Tozun & Özler (2002) estimated the life of the tool using artificial neural network (ANN) for the same experiment and they obtained a better approach of the results than obtained them with the factorial analysis method, as shown Fig. (7).

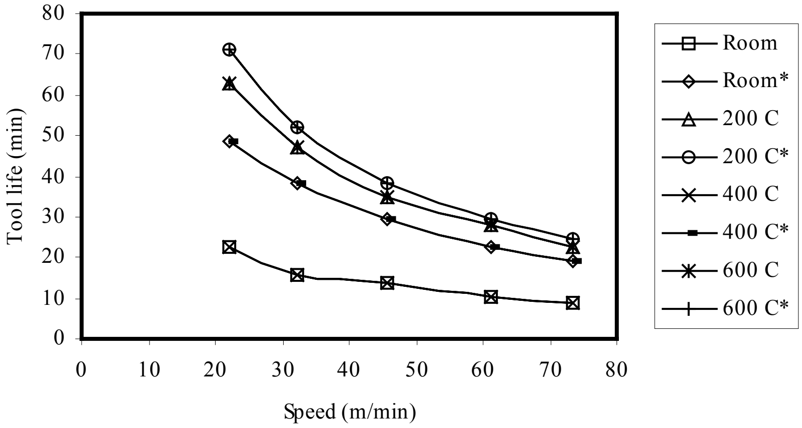


Figure 7. Comparison between the experimental and the ANN (*) results. (f = 0,1 mm/rev; a_p = 1,5 mm) (Özler et all, 2002).

8. Laser assisted machining (LAM)

Energy of the laser can be used in two ways in a machining process:

- The first is the laser assisted machining (LAM), in which the beam heats up the materials to be machined by a conventional tool;
- The second is the laser machining (LM), in which the material of the surface, usually ceramic material, is removed by the vaporization, without employment of the cutting tool. In this case it is not a conventional process.

In LAM, a laser beam is focused in the surface of the workpiece using a group of lens in a point just ahead the edge of the cutting tool, as shown in Fig. (8). In this machining type the heating source can be used of two ways:

In the first case, the laser beam is used to vaporize, melt and resolidify or solutionize the workpiece material with the purpose of improving its machinability without changing the microstructure of the substrate material to a significant degree or depth. This performance is a consequence of the association of the heat flow with the small spot size and the high intensity of the laser beam and the high speed at which the beam sweeps over the surface in a normal machining operation.

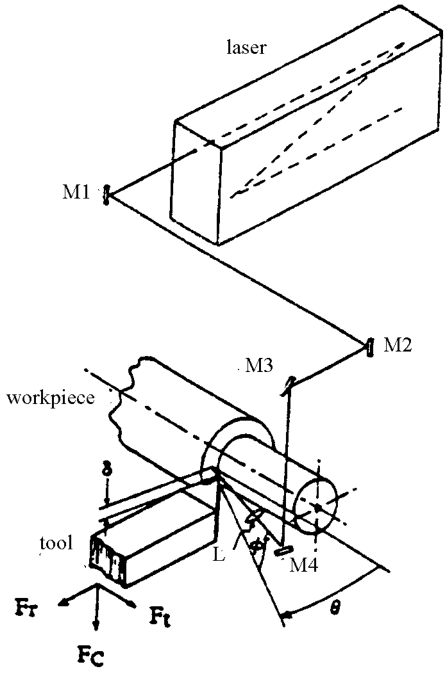


Figure 8. Experimental equipment arrangement for laser assisted machining (Mielnik, 1994).

Vali et all (1998) and Salem et all (1995) used this method with the aid of the energy laser and they got the melt of the material and its removal decreasing the cutting forces and obtaining the tool life increase.

Melting and resolidifying a workpiece material before machining may increases its machinability dissolving hard or abrasive precipitates during melting. Because of subsequent rapid cooling, repricipitation is likely either to be suppressed or to occur on such fine scale as not to damage the cutting tool (Mielnik, 1994).

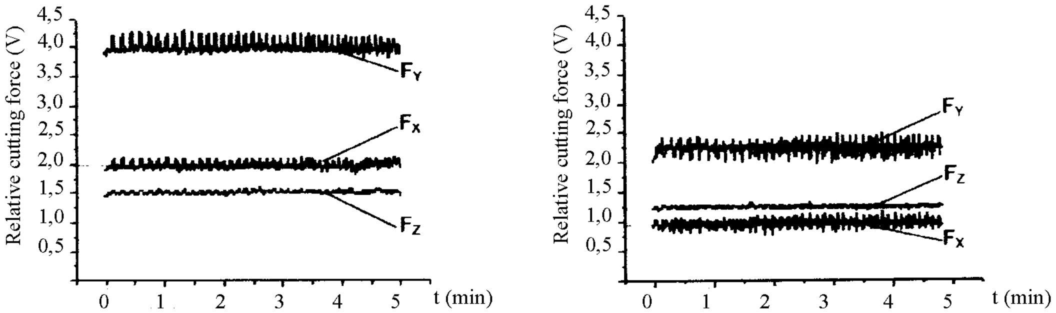
In the second case, with the laser it is possible to heat up on most of the shear plane, without the significant heating of the cutting tool during the chip formation. The heating of the material in the shear plane results in the decreased of the cutting forces, increased of the material removal rate, increased tool life and in the improved workpiece surface finish.

Another fact that can happen in this method is the change of the mode of chip formation from discontinuous for continuous or decrease the tendency to the formation of build-up edge (BUE).

Rozzi et all (2000) developed a three-dimensional thermal model that it was validated comparing the values of temperatures in the surface heated with laser, with the values measured in material removal process using a focused laser pyrometer.

In the turning process of a silicon nitride workpiece, the surface temperature were measured and calculated to determine the effects of the cutting speed, feed rate, the depth of cut, the laser-tool lead distance, and the laser beam diameter and power on thermal conditions. The measurements are in excellent agreement with predictions based on a transient, three-dimensional numerical solution of the heating and material removal processes in a determinate range of temperatures.

Recently, Wang et all (2002) accomplished machining researches with pieces of Al_2O_3 particle reinforced aluminum matrix composite assisted with YAG continuous solid laser. In the experiment, the laser power chosen was 150 W, the distance between the laser heating point and the cutting point was about 10 mm and the feed rate was 0,1 mm/rev. The comparison experiment of cutting forces was performed changing the depth of cut and cutting speed, and they obtained reduction around 50% in feeding force and in the passive force, and the cutting force was reduced by nearly 10%, as showed in Fig. (9). The tool wear was reduced around 20 to 30% and they still obtained an improved surface quality in relation to the conventional machining. Another satisfactory verification in the experiments was that the process can increase the compressive residual stress of the machined surface, increasing the fatigue strength and improving the surface quality.



(a) Conventional cutting

(b) Laser-assisted hot cutting

V = 25 m/min; a_p = 0,3 mm; f = 0,1 mm/rev

Figure 9. Comparison cutting force of conventional cutting and laser assisted hot cutting. (Wang et all, 2002).

Finally, the use of the machining process with laser aid has been justified with base in the cost reduction. Two factors that influence in the reduction of the costs are: the increase of the tool life and the increase of the rate of material removal.

In spite of the obtained results, the use of this technique is hindered by the necessary physical space around the tool machine for its installation.

9. New technique of heating of the workpieces in the hot machining using quartz resistance

Looking for a system of workpiece heating that involves smaller installation cost and occupying smaller space around the tool machine, it is studied the possibility of use of a source of heat generated by the emission of infrared radiation by a quartz resistance, being considered that an important property of this radiation type is the selection of the length wave that heats up an dull piece and not the translucent atmosphere around.

The researches with hot turning using quartz resistance as source of heat comes being developed analyzing its effects in the variables: Power electric of the motor, tool wear, surface roughness of workpiece and the aspects of chip formation in consequence of the depth of cut, of the feed rate, and cutting speed (Mello et all, 2003). Preliminary analysis turning steel of difficult machinabilty (valve steel) indicates an increase of the tool life and reduction of the forces in all of tested cutting conditions.

Besides, has not noticed significant microstructural change in the workpieces and better roughness when compared with the same conditions in process of conventional machining.

10. Summary

The hot machining process is recommended for application in materials of difficult machinability as: hard-to-cut materials, fragile materials, spray or weld deposited metal coatings, or steels that absorbed in its surfaces sand or slag. These types of materials are extremely destructive to cutting tools in conventional machining process.

For heating of the workpieces in the experiments, the researchers used several types of sources of heat, and each one of them presented its advantages and disadvantages.

A common verification in the used methods was that each machined material has an optimum value of temperature to which occurs increase of the tool life, and above this value the tool life decreases, and what determines these values are the properties of each material.

To become viable, is desirable that the hot machining method:

- Does not provoke structural and dimensional alterations in the workpiece;
- Presents speed of heating and quick response to the temperature control;
- Do not be dangerous to operators;
- Does not have high cost
- It is simple, of easy adaptability, and not needs significant physical changes in the tool machine tool;
- Provides the heating in the shear zone, and;
- Provides high density of heat.

Amongst the some used methods the heating are distinguished processes: with electric current between workpiece and cutting tool; with plasma arc; and Laser assisted machining (LAM).

Beyond, of the increase of the productivity, the hot machining process provides in the workpiece the improvement of finish surface, reducing the roughness and, it was possible to observe in the machining of ceramic materials with LAM, the sprouting of residual stress of compression, that had increased the fatigue strength of the piece. Other excellent aspects, are: the alteration of the chip formation of discontinous for continuous, in fragile materials, and the reduction of the tendency of formation of build-up edge (BUE).

In spite of the considerable volume of researches about the hot machining methods, its applications in the industries are limited, because the high costs of the devices for heating of the workpieces and the limitations of spaces for facilities around the tools machines, make unfeasible the adoption of this technology, under the points of views financiers and operational in the lines of industrial productions. However, in the last years, the number of research on the hot machining process increased significantly, mainly with the use of the plasma arc and the laser, similar to make possible turning processes with difficult machinability materials, as advanced ceramic and high strength steel. These materials are machined currently through abrasive process, that presents least rate of removal of materials in relation to the turning.

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