Changes in the metallic polycrystalline material of the surface layers generated by subtractive machining processes

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Résumé:

Dans le domaine de la fabrication de machines, il y a différentes manières d' éliminer l'excès de matériau de la pièce afin d'obtenir une pièce ayant des propriétés spécifiques à son utilisation. Dans le cas des méthodes d'usinage dites classiques, l'excès de matière est essentiellement éliminé sous la pression exercée par l'outil de coupe jusqu'au moment où un phénomène de cisaillement se développe et qu'un copeau est générée. Dans le cas des méthodes d'usinage non conventionnelles, des processus de chauffage localisé du matériau, des réactions chimiques, des processus de micro-fissuration et de cavitation pourraient être utilisés pour déterminer l'enlèvement de matière de la pièce. Tous les processus d'enlèvement de matière de la pièce déterminent les modifications de la couche superficielle métallique polycristalline. L'étude théorique et expérimentale des résultats obtenus en utilisant des méthodes d'usinage soustractives distinctes a montré que ces méthodes d'usinage entraînaient des modifications spécifiques de la microdureté de la couche superficielle, de la structure métallographique, de l'intégrité et de la rugosité de la surface usinée.

Abstract:

In the machine manufacturing field, there are various ways of removing excess material from the workpiece to obtain a piece with properties specific to its usage. In the case of the classic machining methods, the material excess is essentially removed due to pressure exerted by the cutting tool in the direction of movement until the moment when a shearing phenomenon develops and a chip is generated. In the case of nonconventional machining methods, processes of localized material heating, chemical reactions, micro-cracking and cavitation processes could be used to determine the *material removal from the workpiece. All the processes of material removal from the workpiece determine changes in the polycrystalline metallic surface layer. The theoretical and experimental investigation of results obtained by using distinct subtractive machining methods showed that these machining methods lead to specific changes in the surface layer micro-hardness, metallographic structure, integrity, and roughness of the machined surface.*

Keywords: surface layer, polycrystalline material, subtractive machining methods

1 Introduction

In machine manufacturing, the concept of *material processing* generally means the change of shape, dimensions, aspect, even of material composition, in order to produce a part with desired properties.

If *cold processing methods* are considered, a possible classification shows that there are *classical processing methods* (based, essentially, on the use of the plastic deformation effects) and *non-conventional processing methods*. The latter occur when an increase of energy transfers to the work zone, and it either ensures a more efficient application of a classic machining method (such as *example*) or the processing develops on distinct fundamental machining.

Another classification of processing methods could take into consideration *the quantitative changes of the workpiece material*: there are *subtractive processing methods*, *additive processing methods* and *processing methods without noticeable changes of workpiece mass*.

For processing methods resulting in material removal from the workpiece (subtractive processing methods), *machining* is the most well-known term/terminology.

Some of the cold machining processes that are included in the group of non-conventional machining are electrical discharge machining, electrochemical machining, chemical machining, plasma and ion machining, ultrasonic machining, laser beam machining, electron beam machining, machining by means of fluids in movement [1, 2] etc.

If plastic deformation is considered as essential in the case of cutting processes, then plastic deformation is also appreciated as significant in the case of non-conventional machining processes; then, processes connected with other phenomena are applied to remove the excess of the material from the workpiece.

Major changes could develop in the polycrystalline surface layer affected by the machining process as a consequence of the pressure application, of the significant increase of the temperature, of developing chemical reactions or cavitation processes. From the point of view of the manufacturer, it is important that the workpiece layer affected by the processing method is thin as possible or that this layer must have properties adequate to the use of the part.

In this way, in some situations, the researchers were interested in the investigation of phenomena developed in the workpiece surface layer. Another aspect of interest was the thicknesses of the layer affected by the material removal process within the classic and non-conventional machining methods.

For example, Kuzinovski et al. took into consideration the development of a methodology able to offer information concerning the way in which machining conditions exert influence on certain characteristics of the surface layer [3]. They proposed and developed specialized software to be used when applying that methodology.

Mouralova et al. investigated the structure and properties of the surface layer resulted after applying wire electrical discharge machining on alloyed steel [4]. They were interested in highlighting the presence of the diffusion subsurface damages able to affect the service properties of the manufactured part.

Haddadi et al. took into consideration Teodosiu and Hu's physically-based model and applied it to the frame of continuum mechanics based on the internal state variables [5] when considering plastic deformation processes without material removal from the workpiece. They appreciated that the results of their research facilitate the assessment of the work-hardening effect in predicting the stress distribution, and spring-back in the case of several multi-stage forming processes.

As a consequence of applying various machining methods, changes in the surface layer of the workpiece polycrystalline metallic material are expected after applying a certain machining process. Generally, such changes are materialized by obtaining a certain surface roughness, metallographic structure, micro-hardness and stress state. Some changes were the subject of research presented afterwards, taking into consideration the results of several classic and non-conventional machining methods that assume material removal from the workpiece.

2 General ways of developing the process of material removal from the workpiece

In the case of *classic cutting machining methods,* the workpiece material is essentially pressed by the cutting tool until micro-cracks are generated and a shearing phenomenon develops, determining chip formation and, thus, gradual material removal from the workpiece.

In the case of *non-conventional machining processes*, sending an additional quantity of energy strongly focused on the work zone could either contribute to intensifying material removal as a consequence of improving classic machining conditions, either to material removal through processes fundamentally distinct.

The study of fundamental phenomena found in *cold processing methods* where workpiece mass is removed leads to five categories of processes:

1. Processes of plastic deformation; there is a large set of classic machining methods based on chip generation as a consequence of developing plastic deformation processes (turning, milling, drilling, broaching, planning, mortizing, grinding, lapping etc.), but there are also certain non-conventional machining methods based on plastic deformation process developed in the workpiece material (for example, the abrasive component of the ultrasonic machining method or of the abrasive electro-chemical machining, abrasing flow machining, abrasive jet machining, water jet machining and abrasive water jet machining etc.);

2. Processes of localized workpiece material heating to temperatures when the phenomena of melting or vaporizing develop. Such processes are specific to electrical discharge machining, plasma or ion beam machining, laser beam machining, electron beam machining;

3. Processes based on the development of chemical reactions between a chemically-active substance and the workpiece surface layer. The chemical reactions could naturally appear (this is the case of the chemical machining) or they could be initiated and developed as a consequence of an electrical field presence (this is the case of electro-chemical machining);

4. The fourth way in which material can be removed from the workpiece seems to be specific to some non-conventional machining methods and surmises the phenomenon of *cavitation*. The presence of cavitation was emphasized particularly as a component of ultrasonic machining, but it could also appear in other situations when liquids are moved in contact with the workpiece surface layer (these could be the cases of electro-chemical machining with hydrodynamic depassivating, of water jet machining or abrasive water jet machining etc.);

5. A lesser-known process able to generate material removal from the workpiece is also *the micro-cracking process*, or the merger of micro-cracks so that small particles generated by the newly-formed fracture could be detached from the workpiece. One could notice that micro-cracks can be generated both from processes based on plastic deformation (classic cutting methods), from pure non-conventional processes involving material heating or even material hit by abrasive particles pressed against the workpiece surface or accelerated towards the workpiece surface (as the case of ultrasonic machining).

To remove part of the workpiece material, a certain power is necessary; generally, from the quantity of power W_t directed towards the work zone within a machining process, only a part W_{mr} is used to generate the proper material removal from the workpiece:

$$W_t = W_{mr} + W_{slc} + W_d, \tag{1}$$

where W_{slc} is the power that determines the changes in the metallic polycrystalline layer, and W_d – the power dissipated in the tool, workpiece and environment without generating changes to the workpiece mass or in the workpiece surface layer.

If one takes into consideration the hypothesis of simultaneous existence of all five ways of material removal within a single machining process, it is possible to write the total mass m_t of the material removal as a sum of five distinct material removal processes:

$$m_t = m_{pd} + m_{mh} + m_{cr} + m_{cp} + m_{mcp}, \tag{2}$$

where m_{pd} is the quantity of workpiece material removed by plastic deformation, m_{mh} – the quantity of material removed by localized material heating; m_{cr} – the quantity of material removed as a consequence of chemical reactions; m_{cp} – the quantity of material removed by cavitation processes, and m_{mcp} - the quantity of the workpiece material removed as a consequence of the micro-cracks develoment.

The specific power W_{sp} could be defined for each of the above-mentioned processes of material removal:

$$W_{sp} = \frac{W}{m} \tag{3}$$

where W is the power necessary to remove the massic amount m of material from the workpiece.

If we take into consideration the above-mentioned way of calculating specific power, the equation (1) could be written as:

$$m_t = \frac{W_{pd}}{W_{sp\ pd}} + \frac{W_{mh}}{W_{sp\ mh}} + \frac{W_{cr}}{W_{sp\ cr}} + \frac{W_{cp}}{W_{sp\ cp}} + \frac{W_{mcp}}{W_{sp\ mcp}} \tag{4}$$

where W_{pd} is the power used for material removal as a result of plastic deformation, W_{mh} – the power used for material removal as a consequence of the heating phenomenon, W_{cr} – power consumed for material removal by chemical reactions, W_{cp} – the power consumed for material removal by cavitation processes, W_{mcp} – the power able to remove material from the workpiece as a consequence of the micro-cracking processes, while $W_{sp\ pd}$, $W_{sp\ mh}$, $W_{sp\ cr}$ and $W_{sp\ cp}$ and $W_{sp\ mcp}$ are the specific powers needed for each of the five ways of material removal.

If equation (1) is considered, currently there is no machining process able to use all five ways of material removal from the workpiece, but some so-called hybrid machining methods including two or even three possible methods: for example, there are hybrid electro-chemical discharge machining methods that use material heating and chemical reactions. The analysis of current machining methods shows the existence of an ultrasonic-assisted electro-chemical discharge machining method that could use four of the above-mentioned ways of material removal from the workpiece (heating, chemical reaction, cavitation and micro-cracking processes) and it is possible that in the future machining methods will be able to use all the five ways of material removal.

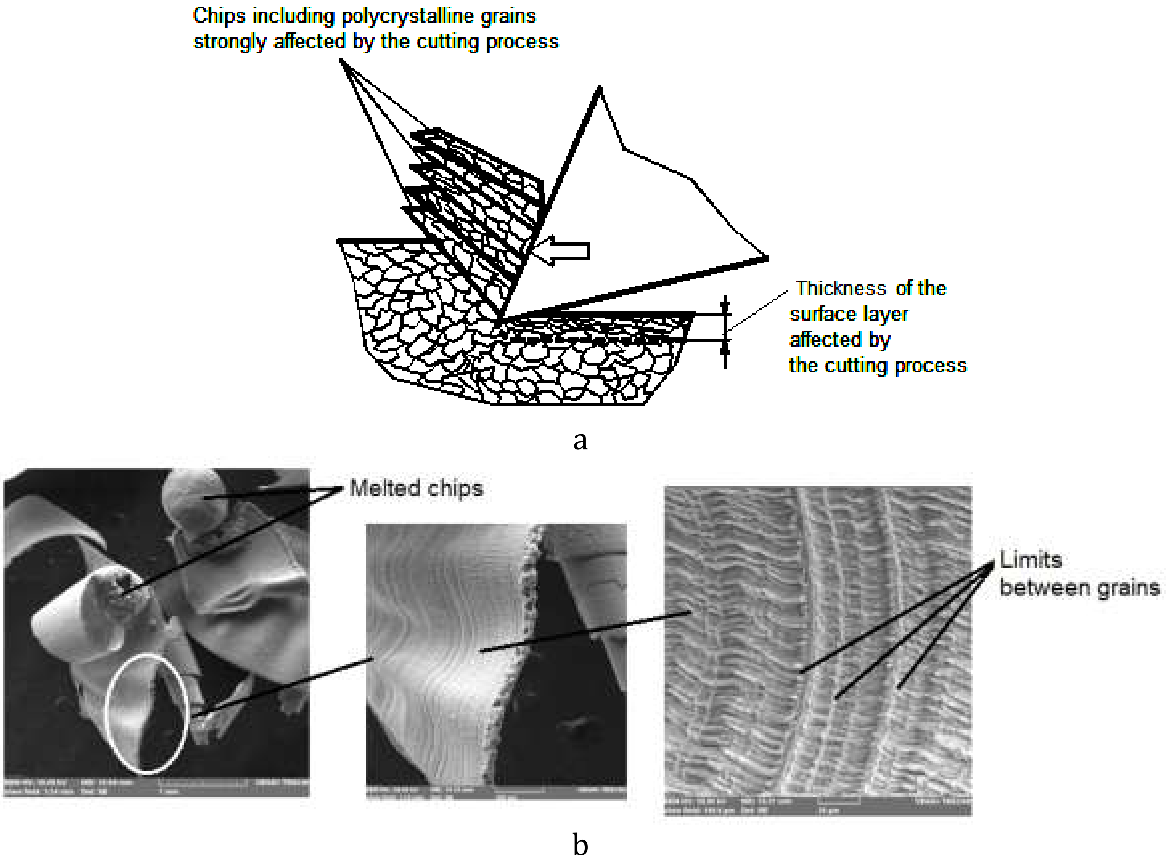
3 Changes in the surface layer of polycrystalline grains during machining based on plastic deformation

As mentioned above, in the case of widely used classic machining methods, the cutting tool exerts a high pressure up to the moment when shearing develops and chips are generated.

The occurrence of shearing under the action of pressure exerted by the cutting tool on the workpiece surface layer was the subject of many researches initiated over the past century. One could mention that as a consequence of intensive plastic deformation, the polycrystalline grains (particularly those from the surface layer) could change their morphology, presenting an elongated shape. The intensive plastic deformation can be also seen in the shape of the chips; in Figure 2 one can see a chip generated during a high-speed cutting process.

The thickness of the polycrystalline top layer affected by machining methods based on the plastic deformation processes is of 0.003 … 0.4 mm [2].

In this chapter only aspects specific to plastic deformation process are analyzed. One must mention that in the case of the high-speed cutting processes or abrasive machining processes, the temperature in the workpiece surface layer could sometimes exceed the melting point of the workpiece material and a heat-affected zone could also appear, with structures corresponding to the phase change.



a

b

Figure 1. Changes in the polycrystalline surface layer in the case of the classical machining methods based on the plastic deformation process : a – schematic representation ; b – chips and chip detail in the case of high speed milling (test piece made of steel X210Cr12, 53 HRC, v=817 m/min, f=0.16 mm/rev, a_p=0.5 mm, image made on the scanning electron microscope Vega II Tescan LSH Tescan) [6].

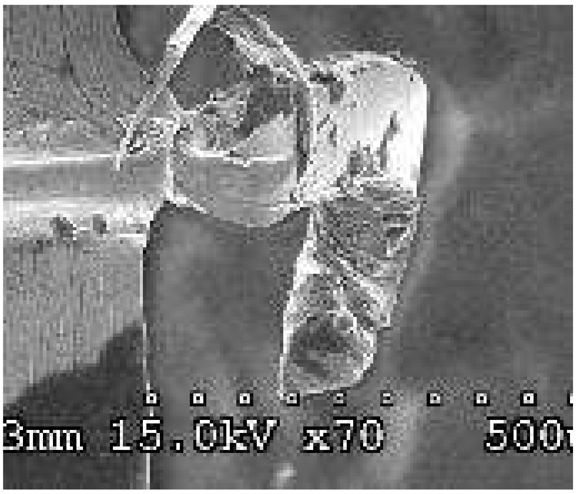


Figure 2. Image of a mono-crystalline material in the zone where the chip is detached during a cutting process where the channel is generated by a single planning stroke (test piece material of monocrystalline copper ; cutting speed *v*= 900 mm/min, depth of cut a_p=0.2 mm; image obtained with a Hitachi scanning electron microscope) [7].

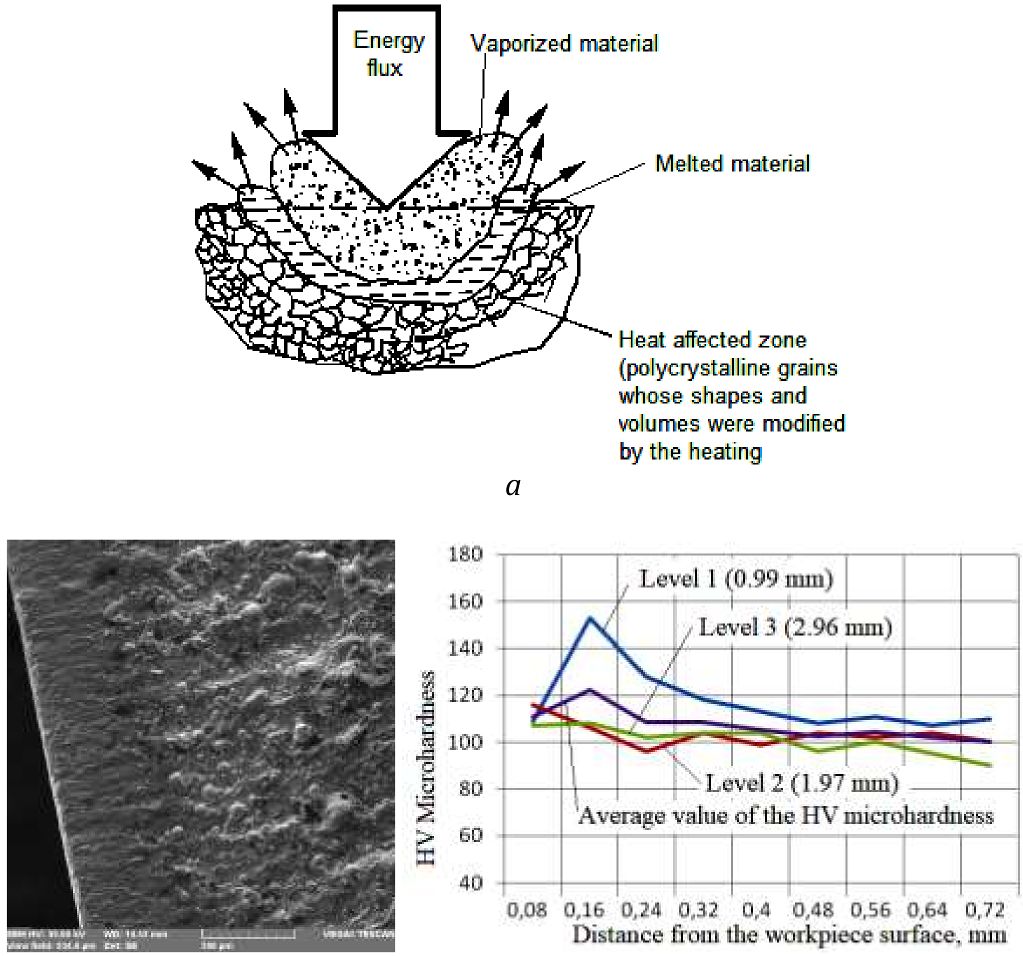
Another example concerning plastic deformation when the test piece is made of a mono-crystalline material (copper) could be illustrated by Figure 2, obtained for the case of planning micro-cutting process in a single stroke, generating a channel; one could see the material pushed in the zone where the cutting tool leaves the test piece material [7].

3 Changes in the polycrystalline grains surface layer for the case of machining methods based on localized material heating

An important group of non-conventional machining processes is based on the localized heating of the workpiece material up to a temperature at which small quantities of material are melted and even vaporized. For example, such a machining method could obtained the localized material heating through the development of electrical discharges between the closest asperities that exist on the tool electrode active surface and the workpiece surface to be machined. Due to the explosive behaviour of the vaporizing process, both vaporized material and small drops of the melted material are thrown outside of the workpiece material in the work gap, from where the circulation of a fluid (usually a dielectric liquid) can remove the material detached from the workpiece and from the tool electrode.

On the other hand, there are some groups of machining methods that use localized material heating as a consequence of the impact of a high energy particles’ beam on the workpiece material. In the case of electrical discharge machining the electrons or the ions are accelerated towards the workpiece surface layer and their penetration of the workpiece material is associated with the local development of intense heating processes. In other cases the impact of photons (for the laser beam machining), ions (for the ion or plasma beam machining) or electrons highly-accelerated towards the workpiece surface (at voltages much higher than those corresponding to the electrical discharge machining processes. Such a phenomenon corresponds to the electron beam machining) is used to ensure an intense localized heating of the workpiece material. As above-mentioned, the small quantities of vaporized material or melted material are removed from the workpiece surface layer. The high temperatures corresponding to this intense heating have, as a result, significant changes in the polycrystalline grains found in the immediate vicinity of the zone where particles hit the workpiece material and a part of this material was removed (Fig. 3. *a*).

It is generally accepted that when a slow cooling takes place after a previous intensive localized heating, in the case of a medium carbon steel, the surface layer affected by heating and cooling could present zones with material that has undergone complex phenomena, such as: resolidified material, overheated material, normalized material, total recrystallized material, partial recrystallized material and, normally, base material that was not modified by the heating process.



a

b c

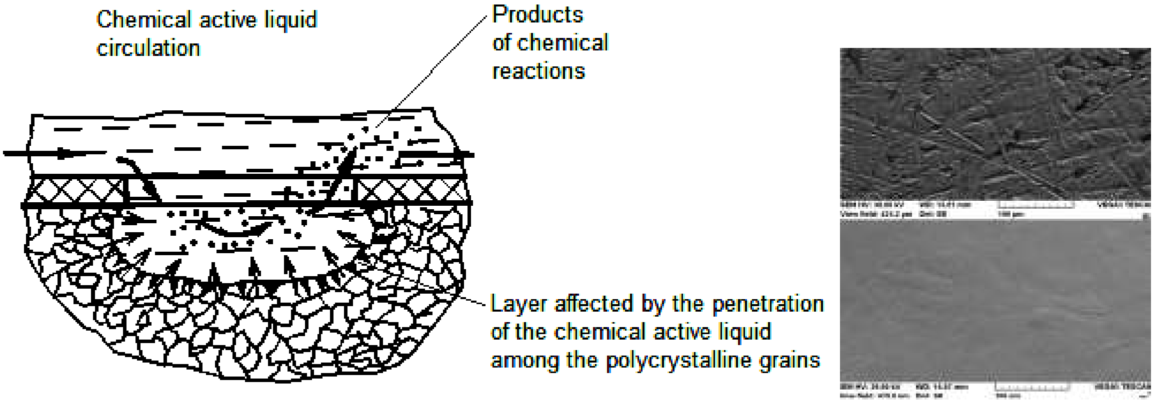
Fig. 3. Changes in the polycrystalline surface layer in the case of the machining methods based on the workpiece localized material heating: *a* – schematic representation ; *b* – aspect of the machined surface, test piece made of steel C30, laser power of 520 W, v=4 mm/s, laser pulse frequency f=120 Hz ; *c* - influence exerted by the distance from the worpiece surface on the *HV* microhardness of the surface layer) [8].

If the cooling process is more intense (for example, under the action of dielectric fluid in the case of electrical discharge machining, or under the action of massive metallic mass of the part in the case of the electron beam machining or laser beam machining), zones of hardened material (in the case of a medium carbon steel) could be met.

The changes in the morphology of polycrystalline grains in the heat-affected layer could be highlighted by a metallographic study or by looking at the changes in the micro-hardness of the surface layer obtained during non-conventional machining based on material heating. For example, in Figure 3. *b*, one could see the changes occurring in the polycrystalline grains from the surface layer affected by processes of heating and cooling when a laser cutting process was used. What is interesting is the fact that not only the distance of the tool from the machined surface is a factor able to illustrate the changes in the polycrystalline grains of the surface layer, but also the distance from the test piece upper surface can also affect the size of the material micro-hardness, as a consequence of various cooling speeds in different directions relative to the machined surface (Fig. 3. *c*).

4 Changes in the polycrystalline grains surface layer in the case of machining methods based on chemical reactions

Chemical and electrochemical machining processes are based on the development of chemical reactions between a chemically-active liquid and the surface of the workpiece material (Fig. 4. *a*). Usually, the liquid containing the removed particles/burrs/removed material as a result chemical reactions is displaced from the workpiece surface due to the chemically-active liquid circulation, so that a passivating layer does not appear. In the graphical representation in Figure 4. *a*, a protective layer was placed on the workpiece surface, which must not be affected by chemical reactions. Such chemical reactions will determine the flow of the material included in the polycrystalline grains into the chemically-active liquid, but the chemical reactions could also affect the different material found sometimes between grains.



a *b*

Figure 4. Changes in the polycrystalline surface layer in the case of machining methods based on chemical reactions developed at the workpiece surface: *a* – schematic representation of the material removal process from the workpiece; *b* – aspect of the surface obtained by electrochemical machining that highlights the non-uniform behaviour of the polycrystalline grains during chemical reactions (test piece material: copper; layer removed by chemical machining with a thickness of 0.11 mm, test duration 80 min, room temperature, chemically-active liquid: aqueous solution of ferric chloride; images obtained by means of the scaning electron microscope before and after the chemical machining, magnificantion: 500 x.

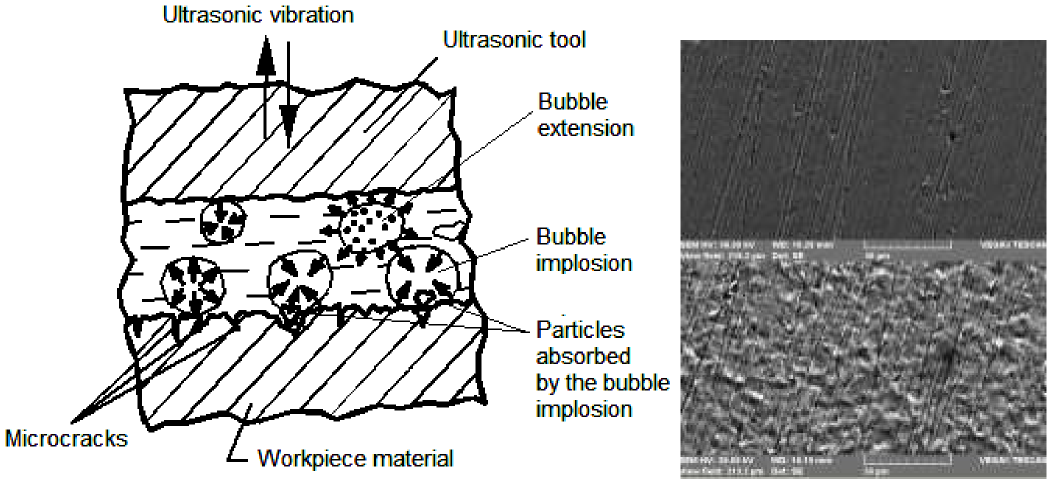
Essentially, the material removal process is more intense in the zones where the differences of electrochemical potential between the particles of the chemical active liquid and the particles of the workpiece material are higher. In this way, it is expected a non-uniform aspect of the machined surface. An image of such a surface can be seen in Figure 4. *b*.

5 Changes in the polycrystalline grains surface layer in the case of the machining methods based on micro-cracking and cavitation processes

The cavitation component of the ultrasonic machining is relatively well-known. Indeed, ultrasonic machining is based on material removal as a consequence of three distinct effects of ultrasonic vibration on a liquid that incorporate abrasive particles: *a) micro-chipping*, determined by the abrasive particles movement in contact with the workpiece surface; *b) micro-cracking*, generated as a result of pressure exerted by the abrasive particles on the workpiece surface; *c) cavitation*, materialized in the breaking and remaking the integrity of the liquid under the action of the ultrasonic vibration. It is possible that cavitation phenomena develop also in the case of other non-conventional machining processes in which a liquid is moved in contact with the workpiece surface; this could be the case of the electro-chemical machining with hydrodynamic depassivating, when the electrolyte liquid has a high pressure and speed, but systematic studies concerning such an aspect are not known to the paper's authors.

An image corresponding to the processes supposed to develop in the work zone in the case of ultrasonic machining can be seen in Figure 5. Under the action of ultrasonic vibration of the ultrasonic tool (in fact, of an auxiliary object, since it does not contribute directly to material), the liquid seems to boil. The liquid breaks in the bubbles of small dimensions and subsequently the liquid integrity is restored.

The generation of the gas bubbles could determine the variation of the pressure exerted on the workpiece surface layer and, thus, micro-cracks could appear in the surface layer. These micro-cracks could diminish the integrity of the zones affected by them. During the implosion of the bubbles, small quantities of the surface layer can be absorbed in the liquid and subsequently removed from the work zone, sometimes also under the action of the vibratory motion of the ultrasonic tool. One could mention that the micro-cracks are not generated only by the bubbles implosions, but also by the pressure exerted by the abrasive particles on the workpiece surface.



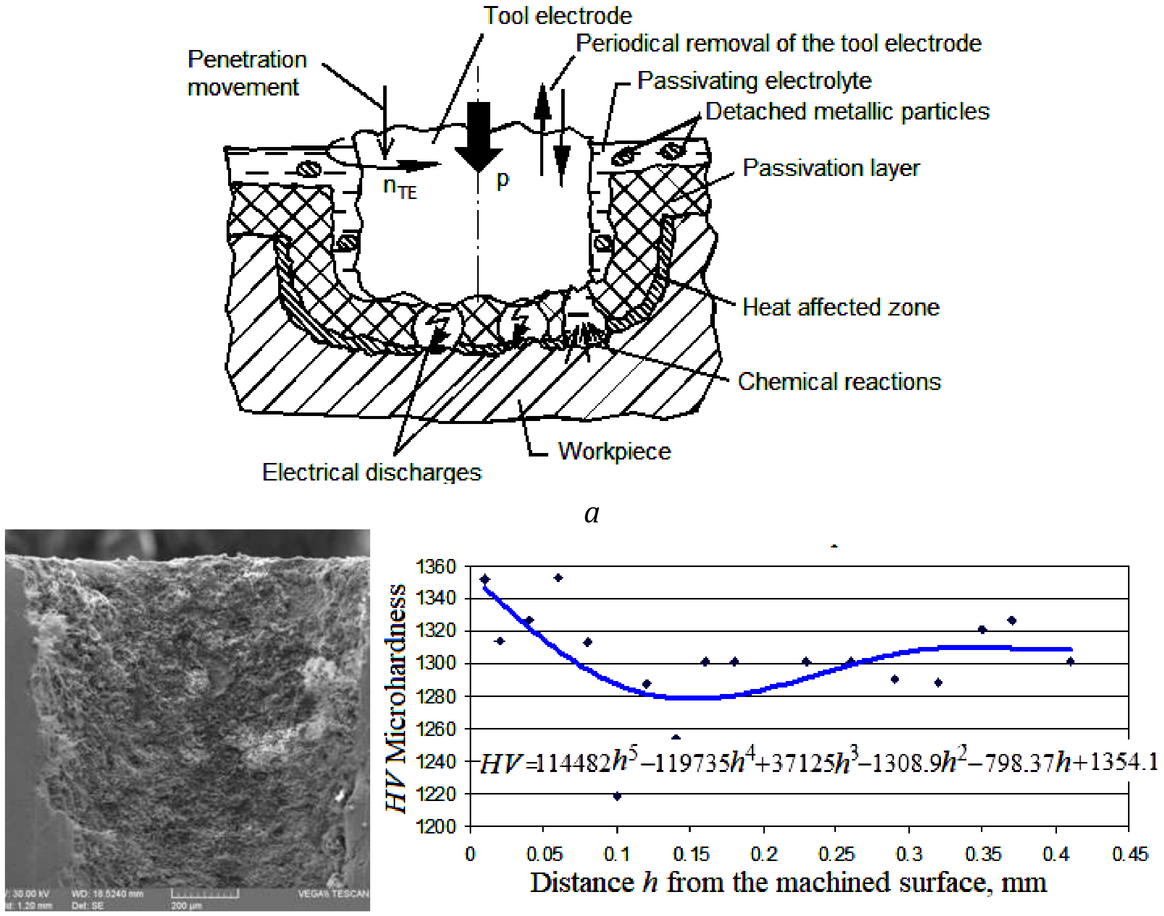
a *b*

Figure 5. Changes in the polycrystalline surface layer in the case of machining methods based on cavitation and micro-cracking processes developed at the workpiece surface: *a* – schematic representation of the cavitation component of ultrasonic machining ; *b* – aspect of the surface layer affected by the cavitation process; the open colour area was affected by the vibration of the ultrsonic tool, placed at a distance of 0.3 mm from the workpiece surface, test piece made of copper, work liquid: water without abrasive particles, frequency f=20 kHz ; images obtained by means of the scanning electron microscope before and after the application of the cavitation process ; magnification : 1000 x.

6 Changes in the polycrystalline grains surface layer in the case of a hybrid machining method

The above-discussed aspects took into consideration only one way of material removal from the workpiece as a result of classic or non-conventional machining processes. The analysis of various phenomena developed in the work zone showed, however, that there are machining processes when two or even three distinct ways of material removal processes could develop and each of them could generate certain changes in the polycrystalline grains found in the surface layer. For example, such a hybrid machining process is *the electro-chemical discharge machining processes*, which uses electrical discharges and chemical reactions to remove small quantities from the workpiece surface layer.

A schematic representation of an electro-chemical discharge drilling process can be seen in Figure 6. *a*. The tool electrode is rotated and pressed on the workpiece surface. Due to the inclusion of the tool electrode and the workpiece in an electrical circuit of direct current, the chemical reactions between the workpiece material and the electrolyte lead to the generation of a passivating layer thicker in the



a

b *c*

Figure 6. Changes in the polycrystalline surface layer in the case of an electro-chemical machining method : *a* – schematic representation ; *b* - surface obtained by hybrid electro-chemical discharge drilling, test piece material: high speed steel HS 6-4-2: voltage U=45 V, capacity C=840 µF, work liquid density ρ_{wl}=1.20 g/cm^3, drilling tool electrode diameter D=0.9 mm; *c* – change of the surface layer micro-hardness [9].

zone where the intensity of the electric field is higher. Under the action of the tool electrode rotation and pressure, the thickness of the passivating layer is diminished down to values when electrical discharges could penetrate the passivating layer and a process of material removal by electrical discharges develops. The electrical passivating layer and in these zones, the chemical discharges interrupt the reactions and could contribute to an additional process of material. In the above-mentioned way, the tool electrode gradually penetrates the workpiece material and a hole is then generated (Fig. 6. *b*).

One could notice that as a consequence of the electrical discharges, at least a heat-affected zone will appear in the hole's surface layer. Certain changes in the surface layer resulted due to the electrochemical discharge drilling process and can be seen in Figure 6. *c*; one could see the change of the surface layer micro-hardness as a result of thermal processes developed during the hybrid electro-chemical discharge drilling process.

4 Conclusions

In machine manufacturing technologies, the excess of material can be removed from the workpiece both by classic and non-conventional machining processes. Distinct phenomena are found at the base of the various classic machining methods and, as a consequence, there are various ways in which changes occur in the polycrystalline grains or in the limits between the grains found in the workpiece surface layers affected by the machining processes. Essentially, it was found that there are five distinct categories of changes that could develop, namely changes generated by plastic deformation, heating, chemical reactions, micro-cracking and cavitation. Frequently, in the case of a certain machining process, only a single way of generating changes in the polycrystalline grains can be met. However, there are situations when two, three or even four ways of generating changes develop; for example, this is the case of several hybrid machining methods. The changes in the surface layer resulted as a consequence of applying a certain machining process could be emphasized by means of the metallographic images, by the variation of the surface layer micro-hardness and indirectly by the changes of the chips dimensions, shapes, and structures. In the paper, a synthesis concerning the ways in which changes occurred in the surface polycrystalline layers obtained by distinct machining methods is presented, using both hypothetical schemes and diagrams and images of the investigated zones. In the future, there is the intention to develop extended experimental researches in order to investigate in more detail the ways in which distinct materials could be affected by the conditions in which the machining process develops.

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