MACHINING METHODS BASED ON THE IMPACT EFFECTS

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Abstract: The concept of *impact* refers essentially to the collision of two bodies; the effects of impacts can be used to materialize machining processes. Thus, just the classical machining methods by cutting are based on the impact of the cutting tool with the workpiece material. The paper analyses the possibilities to consider some classical and non-conventional machining methods as being based on the impact effect. Three types of impact effects are highlighted: mechanical effect, thermal effect and chemical effect. As particles directed to the workpiece surface and which are able to generate impact effects, the abrasive particles, the electrically charged subatomic particles and the photons are considered.
Key words: machining methods, impact effect, mechanical effect, thermal effect, chemical effect.

1. INTRODUCTION

The concept of *manufacturing* refers generally to the action or to the way to produce something by appropriate use of machines, tools and labor. The manufacturing includes also all the intermediate processes needed for the production and integration of the product components. The importance of the manufacturing can be highlighted by considering the manufacturing as an industrial branch whose weight in the world economical activity is of about 25 %. There are manufacturing methods based on the removal of the material from the workpiece, manufacturing methods based on the material addition to the workpiece and manufacturing methods which do not generate significant changes of the quantity of material included in the workpiece.
The machining is a manufacturing method; generally, the machining generates the change of the shape, of the dimensions, of the aspect and eventually of the material constitution, in order to obtain a product having previously specified qualities. The last decades highlighted the use of the concept of machining for the methods involving the removal of the material from the workpiece.
By taking into consideration the modality of the energy transfer to the work zone, the researchers appreciated that there are *classical* or *traditional* machining methods and *non-conventional* machining methods. The last category refers to the machining methods based essentially on increasing the energy available in the work zone, by different ways, so that either a traditional machining process develops under better conditions, or the machining process develops on new principles, fundamentally different in comparison with the basic principle of the traditional machining process.
The concept of *impact* defines the results of the collision of two bodies. Impact phenomena could be met both in the case of conventional and non-conventional machining methods; even the cutting machining methods are based by an initial impact of the tool face with the workpiece material. Of course, there are machining methods at which the specific impact energy is higher, as the case of high speed machining is.
In the case of the machining methods tackled within this paper, only the impact of small bodies acting as tools with the workpiece surface were taken into consideration. One can use the name of *particles* in the case of small granules of solid material; of course, if the dimensions of the particles are lower that 1 mm, their adequate name could be that of *microparticles* and if the particles dimensions are lower than 1 μm, their name could be that of *nanoparticles*. The last name (nanoparticles) could be used in the case of neutral atoms, ions, electrons and photons, whose dimensions are lower just than 1 nm, but one prefer to use here the name of microparticles for all the particles having dimensions of a magnitude lower than those corresponding to an atom.
If the size of the particles which contribute to the impact with the workpiece material is considered, one can find three categories of impact:
- impact phenomena generated by particles including many molecules or atoms; this is the case of some machining methods like *abrasive jet machining*,

ultrasonic machining etc.;
- impact phenomena generated by microparticles having dimensions similar to those of atoms and ions; machining methods like *plasma beam machining* or *ion beam machining* could be included in this category;
- impact phenomena generated by the subatomic microparticles; even the ions are subatomic particles, the machining methods which uses the electrons could be included here (for example, such machining methods are the *electrical discharge machining*, *the electron beam machining*);
- a last group of machining methods is based on the impact of the superlight microparticles, like *photons*; machining methods based on the laser phenomena or even on the non-coherent radiation could be included in this group.

If the impact effect of the particles with the workpiece material is analyzed, the following categories could exist: a) mechanical effects; b) thermal effects; c) chemical effects.

Along the years, the researchers tried to clarify different situations of the impact of the particles and microparticles with the metallic pieces.

Thus, Massey and Burhop tackled the physical aspects specific to the electrons and ions impact with the surface layer in a significant monograph initially published in 1952 (Massey and Burhop, 1952).

Desale et al. studied the erosion phenomena as result of the normal impact between test pieces made of ductile materials and a liquid mixture containing erodents such as quartz, alumina and silicon carbide (Desale et al., 2008). They established an empirical correlation to characterize the erosion wear at normal impact conditions, by taking into consideration the effect of hardness ratio.

Klinkov et al. proposed the classification of the impact phenomena on the basis of particle size and impact velocity; they investigated such phenomena in the case of the so-called *cold spray deposition* (Klinkov et al., 2005).

2. MECHANICAL EFFECT OF IMPACT

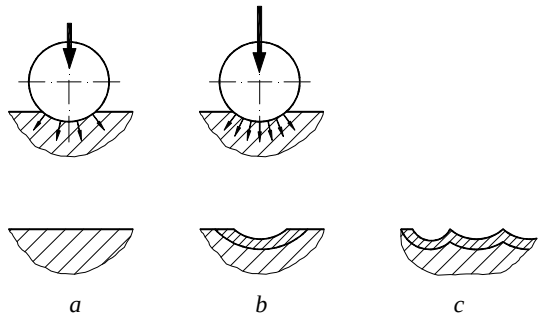


Fig. 1. Impact effect of the particles which do not have sharp edges with the workpiece material: *a* – elastic deformation; *b* – plastic deformation; *c* – aspect of the surface affected by the impact phenomena

Mechanical effects are generally produced by the impact of particles directed to the workpiece surface and having sufficient kinetic energy to exert a significant effect on the workpiece surface layer. It is well known that the kinetic energy *W* of a body found in motion is given by the relation:

$$W = \frac{mv^2}{2}, \qquad (1)$$

where *m* is the particle mass and *v* is its motion speed. The relation (1) highlights the importance of the particle motion speed; the higher the motion speed is, the more intense the impact effect is.

The analysis of the particle impact with the workpiece surface could be made by taking into consideration the presence of the sharp edges on the particles directed to the workpiece surface. Thus, if the particles have not sharp edges and their kinetic energy is small, they do not exert effect on the workpiece surface (fig. 1, *a*). When the kinetic energy is high enough, the pressure exerted by the particle during the impact could exceed the compression strength of the workpiece material and a residual deformation could appear on the workpiece surface (fig. 1, *b*).

The cavity generated by the particles on the workpiece surface could be generally similar to the active surface of the particle; certain differences may be produced by the elastic recovery of the workpiece material after the impact. At the same time, it is known that the plastic deformation generated at the normal temperature is accompanied by *the cold hardening* of the workpiece material; thus, there will be a thin layer of the workpiece material whose hardness is higher than the hardness of the material which was not affected by the plastic deformation (fig. 1, *b*).

The surface resulted as consequence of the impact of the particles with the workpiece material could be considered as a concatenation of small cavities, each such cavity being the consequence of a single or multiple impact (fig. 1, *c* and fig. 4, *a*).

This type of impact effect is used within some machining methods, like *ball peening* (Danilevsky, 1973); the balls are directed to the workpiece surface as result of the centrifugal forces action (Tanasă and Grămescu, 2009) or by means of a transport gas. The surface machining by ball peening has a dynamic character, but an image concerning the diameter *d* of the cavity generated as result of the ball impact with the workpiece surface layer could be obtained by means of a theoretical relation (Arkan, 1965) established by taking into consideration the measuring of the HB Brinell hardness (however, one must mention that the test of Brinell hardness has a *static* character):

$$d = \sqrt{D^2 - \left(D - \frac{2F}{HB\pi D}\right)}, \qquad (2)$$

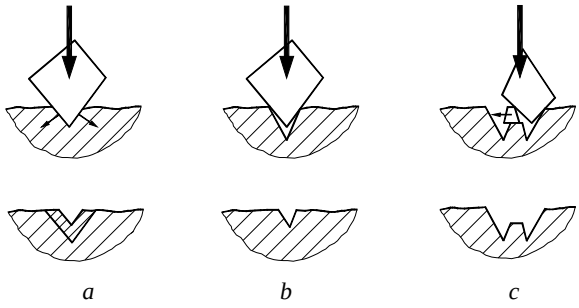


Fig. 2. Impact effect of the particles having sharp edges and perpendicularly directed to the workpiece surface: a – plastic deformation; b – microcracking; c – material removal as result of the microcracking phenomena

where F is the force applied to the ball having the diameter D.

In the case of the particles having sharp edges, two distinct situations could be considered:

a) The situation when the particles are directed to the workpiece surface along a direction perpendicularly on this surface;

b) The situation when the trajectories of the particles are inclined to the workpiece surface.

In the first situation, as above mentioned, if the energy of the particles is not high enough, a significant effect can not be highlighted. When the kinetic energy is sufficient so that the pressure exerted by the particle exceeds the compression strength of the workpiece material, the particle can generate a plastic deformation (fig. 2, *a*), accompanied also by a layer affected by a cold hardening process.

If the workpiece material is fragile, the plastic deformation could become not significant, but a microcrack can be generated (Slătineanu) by the action of the sharp edges on the workpiece surface (fig. 2, *b*). If many such microcracks exist on the workpiece surface, there is a high probability that under the pressure exerted by the particle during the impact phenomenon, the separation and removal of small quantities of the workpiece material occur (fig. 2, *c*). In such a case, the final surface is constituted by a concatenation of the rupture and microcracking surfaces.

In the situation when the particles characterized by the presence of sharp edges have an inclined direction to the workpiece surface and sufficient kinetic energy, they could generate a microcutting process

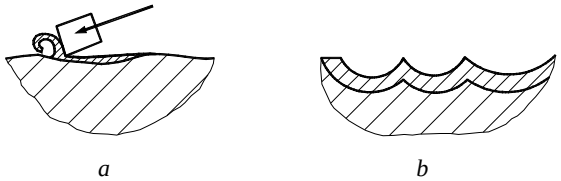


Fig. 3. Impact effect of the particle having sharp edges and directed to the workpiece surface in an inclined trajectory

(fig. 3, *a*). Even the thickness of the microchip is very small, a thin layer could be affected by the cold hardening effect. The surface could be considered as a concatenation of cavities mainly generated by the microcutting processes (fig. 3, *b*); however, certain zones of the machined surface could also be the result of the plastic deformation of the workpiece surface layer, because statistically not all the particles directed to the workpiece have adequate positions to ensure the developing of the microcutting process. On the other hand, if the workpiece material presents also a certain fragility, some microcracks could appear as result of the impact phenomena. The

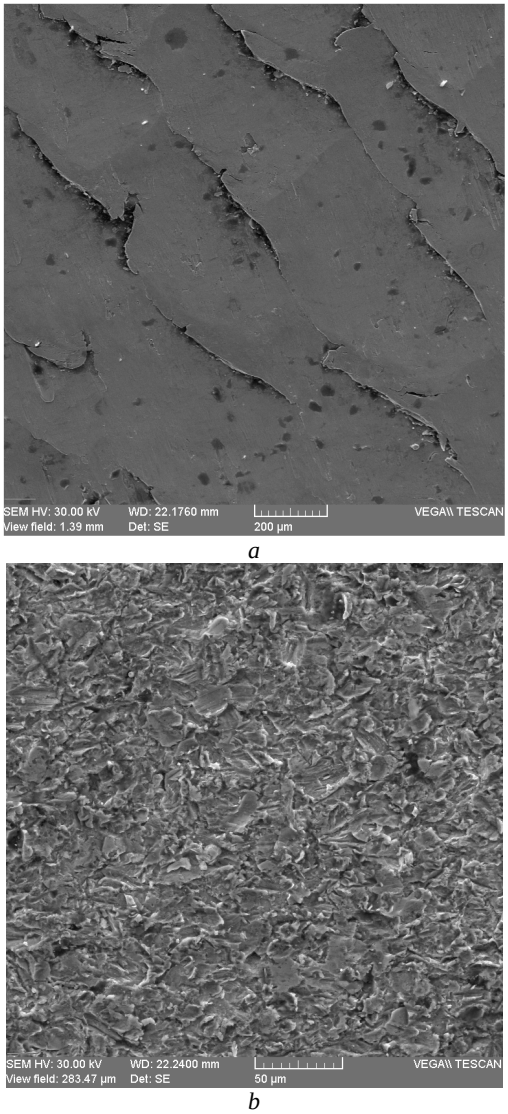


Fig. 4. Surfaces obtained by ball peening (*a*) (SEM image; 200x magnification) and by abrasive jet machining (*b*) (1000x magnification)

material removal by microcutting processes are used within some machining techniques such as *abrasive jet machining*, *abrasive polishing* or *cleaning*. In figure 4 *b*, an image of the surface affected by an abrasive jet machining process (sanding) is presented. Abrasive particles of aluminum oxide having an average dimension of 0.13 mm were directed to the surface of a test piece made of stainless steel.

3. THERMAL EFFECT OF IMPACT

If the impact is generated by subatomic microparticles, the main effect derives from the change of the kinetic energy into thermal energy. If the kinetic energy of the microparticles directed to the workpiece surface is given by the relation (1), it is clear that not all this energy is transformed in thermal energy, a part of the kinetic energy being necessary for the afterward motion of the particles. In such conditions, the following relation could be written for the thermal energy:

$$W_t = k\frac{mv^2}{2}, \qquad (3)$$

k offering an image about the part of the kinetic energy which is transformed in thermal energy.

Impact of electrically charged particles. The main such particles (electrically charged) are *ions* and *electrons*. Generally, these microparticles are obtained by processes specific to the plasma generation; it is known that the main way to obtain plasma in industrial conditions is constituted by the electrical discharges. Indeed, the electrical discharges produced in gases found at normal or slow pressure determine the molecules dissociation and obtaining of the positive ions and electrons. Due to their electrical charge, both the electrons and ions could be firstly extracted from the plasma and directed/accelerated to the workpiece surface. Free electrons could be also obtained by the heating of some materials and this way is used, for example, in the case of *the electron beam machining*.

Electrical or electromagnetical devices could be afterwards used to direct the electrically charged microparticles to the workpiece surface or at least to those surfaces which are not protected with insulating layers. Due to their small dimensions, the electrons could initially penetrate a thin surface layer, without to obtain significant effect from the point of view of the machining method. The thickness of this layer is given by the Shenland's relation:

$$\delta = 2.2 \cdot 10^{-12}\frac{U^2}{\rho}\ [\text{cm}], \qquad (3)$$

where ρ is the material density, in g/cm^3 and U is the acceleration voltage, in V.

If the electrons energy is high enough to continue their trajectories at depths higher than the dimension defined by the Shenland's relation, the electrons are able to transfer their kinetic energy to the atomic structures (atoms, molecules) of the workpiece material. This means that the amplitude of the atomic structures oscillations round to their equilibrium positions increase and this fact is materialized by the increasing of the temperature. If the temperature is high enough, a so-called *thermal source* appears and the workpiece solid material is transformed in melted material or even in vapors. As result of the explosive increasing of the material volume affected by melting or vaporizing phenomena, the pressure exerted on the layer initially crossed by the electrons also increases, and this thin solid layer is destroyed, permitting the throwing of the melted and vaporized material out of the workpiece. This situation is specific to the case when the energy transferred to the workpiece material is high enough; otherwise, only effects of melting or changing of the metallographic structure develop. If the electrons are generated and directed to the workpiece surface in a gas at low pressure, they could constitute a so-called *electron beam*, whose straightness could be adequately modified by electrical and electromagnetical means. The positive ions are used within some machining methods such *ion beam machining* or *plasma beam machining* are.

As previously mentioned, the ions could be obtained as result of the electrical discharges. Due to their positive charge, the ions are attracted by the negative charged bodies and, as consequence, they are directed to the surface of the workpiece connected to the negative pole of a direct current supply.

There are different modalities to use the ions to materialize a machining process. Thus, the most known modality is specific to *the electrical discharge machining*, when the electrode tool is connected to

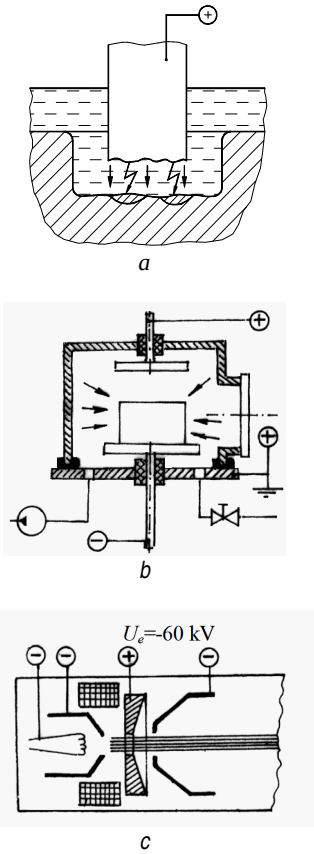


Fig. 5. Obtaining of the positive ions and their directing to the workpiece surface in the case of electrical discharge machining (*a*), ion machining (*b*) and ion beam machining (*c*)

the positive pole of a direct current supply and the workpiece is connected to the negative pole of the same supply.

The electrical discharge is practically materialized by

a plasma channel appeared between the closest asperities of the electrodes; within this channel, the electrons are directed to the electrode tool surface and the positive ions to the workpiece surface (fig. 5, *a*). This phenomenon is specific to *the electrical discharge machining*, when the workpiece is connected to the negative pole of the direct current supply.

Other machining methods based on the use of the positive ions develops in adequate precincts characterized by low pressure; the voltage applied to the positive electrode and to the workpiece (connected to the negative pole of the direct current supply) determines the motion of the positive ions to the workpiece surface (fig. 5, *b*); this is the situation of the *ion machining* in precincts.

The third way to use the ions implies the existence of more complex equipments (fig. 5, *c*), in which the electrical discharge is generated between the thermocathode and the anode. From the plasma thus generated between the thermocathode and anode, the ions are attracted by the extraction electrode, which is connected to a high negative voltage (-60 kV). As result, an ion beam is generated and this beam could be directed to the workpiece.

If the electrons could penetrate a thin surface layer without a thermal transfer to be developed, this situation is not valid in the case of the ions directed to the workpiece. The higher dimensions of the ions (in comparison with those of the electrons) ensure the immediate change of the ions kinetic energy in thermal energy; because the amplitude of oscillations of the atomic structures existing in the workpiece surface layer increases.

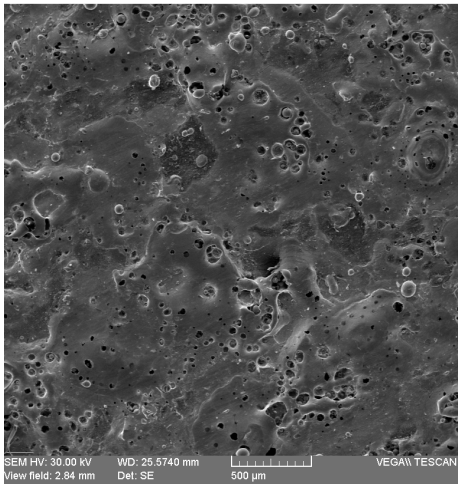
A larger set of machining methods is specific to the principle of ion or plasma machining; in such cases, the ions could be used for cleaning, material removal, alloying, deposition etc.

In figure 6, two images corresponding to the aspect of surfaces obtained by electrical discharge machining are presented. While the image from the figure 6, *a* is the result of the ions impact with the workpiece surface, the image of the figure 6, *b* shows the surface obtained as result of the electrons impact with the workpiece surface. The both surfaces were obtained by using the same operating conditions (pulse time t_i=420 μs, off time t_{off}=60 μs, average current intensity I=56 A, machining equipment type Sodick AD3L etc.) and changing only the polarity of the electrodes. One can notice that the aspects of the machined surfaces by the ions and electrons are similar, but the results of technological interest are distinct; for example, the material removal rate is higher of about 8 times in the case of the workpiece connected to the negative pole, when the machining process is the result of the ions impact, in comparison with the situation when the workpiece is connected to the positive pole and when the electrons impact determines the material removal from the workpiece.

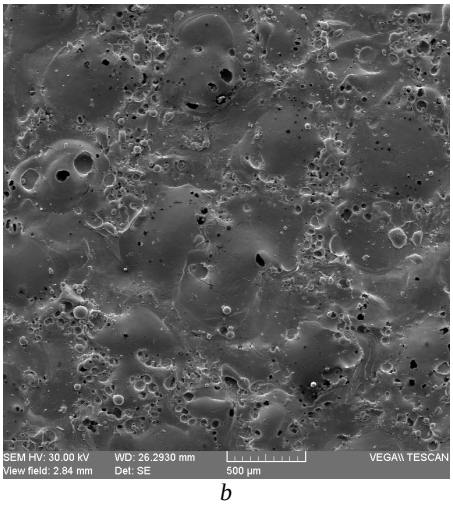
Impact of subatomic microparticles which have not electrical charge. The main microparticles having dimensions comparable with the dimensions of an atom and which have not electrical charges are *the neutral atoms* and *the photons*.

The neutral atoms could be directed to the workpiece surface as result of the collisions with the ions which are currently directed to the workpiece surface; in their trajectory to the workpiece connected at the negative pole of a direct current supply, the positive ions could collide the atoms and some such atoms could be directed to the workpiece surface. Usually, in accordance with the above mentioned considerations, the effect of the neutral atoms impact with the workpiece surface can be considered as similar to that generated by the impact of ions; differences could appear due to the lower kinetic energy of the neutral atoms.

A second category of subatomic microparticles able to generate thermal effect at their impact with the workpiece material are the photons. Of course, non-coherent photons radiations are sometimes used to materialize a machining process, but nowadays the coherent photon radiation (the *laser* phenomenon) is



a



b

Fig. 6. Surfaces obtained by electrical discharge machining, as consequence of the impact of electrically charged microparticles with the workpiece surface layer: *a* – impact of the positive ions; *b* – impact of the electrons (SEM images – 100x magnification)

more frequently applied within different machining methods. The laser beam could be obtained in distinct ways; in the laser beam machining equipments, the laser radiation is obtained either by optical pumping or by electrical discharge pumping. From the laser source, the laser radiation is directed to the workpiece surface by means of the optical mirrors and lens; a current solution is based on the use of optical fibers.
If the intensity of the laser radiation is high enough, the direct effect of the photon impact with the workpiece surface layer is the increasing of the temperature in the zone of contact between the laser beam and the workpiece material.

4. CHEMICAL EFFECT OF THE IMPACT

Other impact effect of technological interest which is applied within machine building is the chemical effect.
When subatomic microparticles are directed to the workpiece, chemical reaction could be produced and in this way a chemical effect could be observed.
Thus, there are chemical effect in the case of some processes of impact of the ions with the workpiece material; such an effect is used, for example, within *the ion nitriding* applied to increase the hardness and the wear resistance of the pieces or tools made of steel.
The nitrogen ions directed to the workpiece succeed to penetrate the surface layer and to chemically react with the iron atoms, to create iron nitrides, able to significantly contribute to the increasing of the surface hardness. The other category of electrically charged particles directed to the workpiece surface can be the electrons.
Thus, an engraving method based on the use of the electron beams is known. To apply different other machining methods only on certain surfaces of the workpiece, the other surfaces are covered with a protection material, which can be the so-called *electronoresist.* The zones affected by the electrons impact with the electronoresist layer changes their internal chemical composition, so that, in next stage, these zones are removed from the workpiece, permitting the applying of other machining process.
A similar situation can be met in the case of the laser applying; in this case, the workpiece surface layer is covered with a so-called *photoresist layer*, whose chemical composition is locally modified under the action of the laser radiation. Afterwards, the photoresist can be also removed from those surfaces where in the next stages other machining processes can be applied.
The chemical effect of the impact of the coherent photons with different materials can be used within machining processes such as *laser chemical engraving, rapid prototyping by selective laser sintering* etc.

5. CONCLUSIONS

Some of the current machining processes can be considered as based on the impact effects of particles directed to the workpiece material. One of the main effects of this impact is the mechanical effect, which is applied, for example, in the case of the abrasive jet machining or of other machining processes which use free abrasive particles. An impact effect which is widely used nowadays is the thermal effect; this effect is applied to remove the material or to change the metallographic structure of the workpiece material in the case of the many laser beam or electron beam machining methods. The chemical effect of the microparticles impact with the workpiece is considered as useful especially in some hybrid machining methods, to modify the chemical composition of the layers affected by the impact. The paper proposes an integrating way to analyze the use of the impact effect within some machining methods. In the future, some theoretical researches could be developed to model the aspects specific to the impact effects.

AKNOWLEDGEMENT

The research was carried out by researchers from Romania as part of project no. ID_625, financed by the National Council of Scientific Research for Higher Education (Romania).

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Received: 19 November 2009 / Accepted: 20 December 2009 /
Abstract published online: 15 January 2010
© International Journal of Modern Manufacturing Technologies