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STATE OF THE ART OF MICRO-CUTTING

Optimizing each processing process requires a clear knowledge of the mechanisms by which it takes place. In the case of steel processing by cutting, in the middle of the 1940s, a clear model was established according to which the process of chip formation takes place [1, 2]. Based on this model, it was later possible to optimize machining [3-7], with the aim of more efficient steel machining in terms of time spent, better machined surface quality and increased tool life. The established chip formation mechanism is valid only in the case when processing homogeneous materials, materials that are not brittle in nature and where the value of cutting depth is significantly higher than the value of the tool radius, thus its influence on the machining process can be neglected.

When it comes to micro-cutting, there are two approaches by which it is defined [8]:

First approach:

- micro-cutting is a set of all operations that are performed on components of micro/meso dimensions and products in the range of 100 μm up to 10 mm;
- micro-cutting characterizes the requirements for the production of high-precision products, complex geometric shapes from a wide range of materials in a defined range of measures;
- micro-cutting involves the use of special tools (micro tools with a diameter of 50 ÷ 500 μm), small chip thickness (submicron to several micrometers) and speed (50k ÷ 200k min-1).

As a consequence, the main difference between micro and macro-cutting is the dominance of sliding and scratching over shear and the need to take micro-structural effects into account.

Second approach:

The definition of micro-cutting from the point of view of chip thickness dimensions can be classified into:

- Macro: machining in conventional modes where the thickness of the chip is an order of magnitude greater than the tool tip radius and the process is dominated by shear. In doing so, the micro-structural effects can be neglected. The value of chip thickness is above 10 μm;
- Micro/meso: this processing is characterized by the dominance of scratching, friction, elastic and plastic deformation with the conclusion that the tool tip radius is approximately equal to the thickness of the chip. The thickness of the chip ranges from sub micro to several micrometers;
- Nano: this term is usually associated with ultra-precision machining with diamond tools that have the ability to sharpen without a radius or with a small tip radius so that the thickness of the chip can be in the nanometer range.

Industries such as automotive, special purpose, food and others, not infrequently need to introduce newer, more modern materials during product design, and later their production from them. Materials such as various types of glass, ceramics or stone-based materials are on the list of materials often used in the mentioned industries. They have found application from MEMS systems to various types of lenses, and even moving elements that must have good thermal properties and wear resistance. These materials, which are brittle in nature, are classified as very desirable, thanks to their high hardness and good thermal characteristics. However, the introduction of materials of this type in various industries, regardless of all its positive characteristics, has its downsides, which are the difficult machinability of these materials, as well as insufficient knowledge of the mechanisms by which it takes place.

Due to its hardness, the processing of brittle materials takes place at much smaller depths compared to materials that have more pronounced plastic properties. By reducing the cutting depth to one millimeter or less, the machining process shifts from the macro domain to the micro-cutting domain. When it comes to micro-cutting, it can be said that the set cutting mechanisms are no longer valid. Among the main causes are some of the factors such as: pronounced brittleness of the material being processed, rounding of the tool tip whose radius in this case is greater than the depth of cut and inhomogeneity (heterogeneity) of the material being processed. The mechanism of micro-cutting of brittle materials, which by its nature clearly defines the process of chip formation and the conditions under which it takes place, is still not clearly and precisely defined.

What is additionally interesting is that although the mentioned types of materials are brittle in nature, they can be processed in the so-called plastic deformation regime (ductile mode), where the processing is performed without the presence of destruction [9-13]. In the ductile mode, no separation of the material is noticed, but the complete processing takes place thanks to the return elastic and plastic deformations. This type of processing is desirable because it does not require post-treatment to ensure a smooth, transparent surface, or even to remove residual cracks that occur during the cutting process, which could jeopardize the integrity of the structure itself.

Not so long ago, more complex research in the field of micro-cutting was started. All this research is conducted in three basic directions:

- identification of the indentation process under static and dynamic force and the micro-cutting process;
- examination of the influence of the kinematics of the micro-cutting process on the machinability of brittle materials;
- examination of the influence of tool geometry on the micro-cutting process.

Identification of the indentation process under static and dynamic force and the micro-cutting process

In order to clarify the phenomena that occur during the micro-cutting process, the researchers conducted indentation experiments under static and dynamic indentation force, and the micro-cutting (scratching) process with an appropriate cutting tool. The main goal of these experiments was to: explain the mechanism of chip formation, to reach the value of the critical depth of tool penetration, to determine the values of force intensity and specific energy of micro-cutting as a function of tool geometry, speed and depth of micro-cutting.

Unlike materials with pronounced plasticity, where during micro cutting the material is separated in the form of extrusion [14-24], in brittle materials this process takes place by the mechanism of brittle destruction. The process of brittle destruction takes place through the phenomenon of cracking in the cutting zone, then the separation of parts of the material, accompanied by the appearance of crushing of the material. Research aimed at examining the shape and manner of crack formation within the material dates back to the mid-1970s [25-29]. Cracks that form in the cutting zone can be classified into three basic forms:

- medial cracks,
- lateral cracks,
- radial cracks.

Prediction of the intensity of material destruction, i.e., crack growth during the micro-cutting process is necessary for the formation of a valid micro-cutting mechanism. Residual cracks and their unwanted growth within the material can lead to significant side effects. Their presence within the material after the processing process can affect the integrity of the structure, while their uncontrolled growth can lead to undesirable quality of the machined surface. One of the methods for predicting crack length was presented by B.R. Lawn and M.V. Swain [30]. Their research was based on the indentation of indenter under static force. By processing the experimental results using the "Boussinffeesq" method, they found that there is a proportionality between the values of the indentation force and the crack length that occur within the material during and after the indentation process.

Further research B.R. Lawn conducted with his associates [28, 29, 31-33], found that the residual stresses present within the material after the completion of the indentation process are responsible for the further growth of the medial cracks and after the unloading of the material. One of the causes of residual stresses is the heterogeneity of the material being processed. More precisely, the different hardness of the minerals of which the material is composed can be the initiator for residual stresses. The same conclusions were reached in research [34, 35].

A. Chandra et al [36] presented their model for predicting material destruction. Experimental analysis confirmed the great matching of the model with the obtained values. However, what must be singled out, and what has been established by their research, is that the growth of lateral cracks occurs during the unloading of the material. On the other hand, B.R. Lawn and A.G. Evans [27] presented a model for predicting the growth of medial/radial cracks that provides a functional relationship between the size of the critical value of the crack and the indentation force, necessary for the continuation of further crack growth.

In addition to the method of indentation under static force, in previous research, the method of scratching was also used. The main difference between this method and the indentation is that due to the interaction of the tool and the workpiece, both the normal (Fn) and tangential (Ft) components of the cutting force occur. Experiments based on the method of scratching [37, 38], aimed to establish the relationship between the range of plastic deformation depending on the processing parameters, i.e., the relationship between the ductile mode and cutting speed.

All these researches have a similar goal, and that is to find and describe precise mechanisms that explain the phenomena created in the process of micro-cutting of brittle materials. S. Malkin and T.W. Hwang [39].

In the micro-cutting mechanism itself, a very important influencing factor is the depth of cut, and the influence of elastic deformations of the material. The depth of cut is in direct correlation with the cutting mode (ductile or brittle fracture mode) in which the micro-cutting process takes place. This has the consequence that the amount of material removed in the process of micro-cutting of brittle materials is a direct function of the depth of tool penetration. G. Subhash et al. [40] tried to find a method that can be used to determine the mode in which processing is currently performed. The research was based on the analysis of the values of forces that occur during micro-cutting using the "data dependent system (DDS)" method. The main goal was to determine which of the two modes is currently being processed, depending on the intensity and character of the cutting force.

A clearer picture of crack formation and shear planes during the micro-cutting process was examined by D. Ghost et al. [41] using a combined "Boussinesq" and "Cerruti - field solution" method. The experiments were performed on Zirconium Diboride-Silicon Carbide composite material. In addition to these studies, R. Anton [42] and D. Ghost [43] conducted a similar analysis, but on a different material, with the aim of determining the change in mechanical properties of the material during indentation under static and dynamic force.

Researchers [44-48] based their experiments on the development of a mathematical model of micro-cutting of brittle materials. By implementing these algorithms in software packages, which deal with finite element methods, the possibility of predicting the phenomena that occur during the micro-cutting process is realized.

Examination of the influence of the kinematics of the micro-cutting process on the machinability of brittle materials

In the 1950s of the last century, research on the influence of tool trajectory on the machinability of materials began [49, 50]. However, expansion in this area began only in the 1990s when T. Moriwaki et al [51, 52] conducted a micro-cutting experiment with oscillatory tool movement. It was then determined that in relation to conventional cutting of brittle materials, where the tool performs a relatively rectilinear movement in relation to the workpiece, the range of ductile mode can be increased by applying vibratory (oscillatory) movement of the tool. This has also been confirmed in research [53-55]. This type of micro-cutting leads to a decrease in the intensity of forces that occur during the machining process, as shown by M. Zhou et al. [56].

V.K. Astashev and V.I. Babitsky [57] came up with a mathematical model that arrives at the value of the cutting force intensity as a function of the vibrational micro-cutting parameters.

Micro cutting, in which the tool achieves a complex oscillatory movement, requires a special tool geometry in order to achieve the desired movement. Among the first to develop such a system were L. Hahn and co-workers [58]. Their system is specific in that it has the possibility of error compensation. However, one of the problems that occurs with this type of micro-cutting is keeping the tool in a resonant state if there is a change in the intensity of the cutting forces. V. I. Babitsky et al [59] developed a mechatronic system by which the tool is maintained in a resonant state regardless of the change in the value of the cutting force intensity.

Although the oscillatory movement of the tool increases its lifespan, due to the intense friction between the flank surface of the tool and the machined surface of the workpiece, more intensive wear of the flank surface occurs. By changing the direction of oscillation of the tool, which avoids contact of the tool with the workpiece in the return, and to a large extent in the working stroke, there is an additional increase in tool lifespan, as shown by M. Jin and M. Murakawa [60].

T. Moriwaki and E. Shamoto [61-63] conducted an upgraded vibration cutting experiment, the so-called elliptical vibration cutting. For the purposes of this type of experiment, where the tool achieves vibrational elliptical motion, a special tool system was developed and presented by E. Shamoto [64]. In order to obtain greater flexibility during the performance of experiments, the developed system had the possibility of independently defining the oscillation amplitudes in two directions, which achieves the desired orientation of the tool oscillation. This type of micro-cutting has determined that the service life of the tool increases in relation to the rectilinear vibratory micro-cutting. Also, during machining of grooves in brittle materials with elliptical movement of the tool, a better geometry of the groove is achieved in relation to the processing where the tool performs a rectilinear oscillatory movement [65].

Processing of materials with pronounced plastic properties is characterized by obtaining a better-quality surface [66]. N. Suzuki and co-workers [67] by applying the elliptical movement of the tool managed to realize the processing of molds for casting lenses made of Wolfram alloys, which was not feasible until that moment. On the other hand, C. Ma et al [68] found that scraping achieves better machining accuracy compared to conventional scraping, even when the tool achieves rectilinear oscillatory motion. In addition, this eliminates the possibility of cracking at the edges of the workpiece [69].

The values of the force intensities that occur in the contact of the tool that achieves the oscillatory elliptical motion and the workpiece are reduced in comparison with the values of the force intensities in the conventional movement of the tool. Models for precise prediction of force intensity have been presented by both N. Negishi [70] and C. Ma [68, 69].

N. Suzuki and co-workers [71] developed a system for controlling the depth of cut with the help of oscillation amplitude variation. This method has increased the efficiency of such a system. The development of similar systems can be found in other researchers [72, 73].

Examination of the influence of tool geometry on the micro-cutting process

In addition to examining the effect of forces during the process of indentation/micro-cutting, as well as the process of material separation, research has focused on examining the influence of tool or indenter geometry on the process of micro-cutting/material separation. Unlike macro-cutting, where the depth of cut is significantly greater than the value of the tool tip radius, and therefore its impact can be neglected, this is not the case with micro-cutting. The rounding of the tool tip is a very influential factor that affects the micro-cutting process itself, bearing in mind that the value of its radius is greater than the value of the depth at which the tool penetrates the material. As a consequence, the value of the rake angle of the tool changes, which is a function of the depth of cut and the value of the tool tip radius. The change in the value of the rake angle has a direct impact on the increase or decrease of compressive stresses in the cutting zone, as a result of which the process of chip formation can differ in different zones of cutting depth.

Examining the influence of tool geometry on the micro-cutting process has been far more investigated on materials with pronounced plastic properties, compared to materials that are brittle in nature.

Z.J. Yuan [74] examined in detail the influence of the tool tip radius value on the critical penetration depth for a material with pronounced plastic properties. He primarily based his research on the observation of the dependence of the critical depth that leads to the formation of chip in the form of extrusion from the value of the tool tip radius. It turned out that a tool with a smaller value of the tool tip radius leads to a reduction of the limit below which there is no separation of material. Below the critical values of the depth of micro-cutting, the material is elastically and plastically deformed. This can be explained by the change in the effective value of the rake angle proved by Z. Fang in his work [75]. His research has shown that the effective value of the rake angle, which is a function of the value of the depth of cut and the tool tip radius, has a significant influence on the direction of propagation of the stress field within the material. Many subsequent studies have been conducted on a similar topic [76-82].

Changing the geometry of the tool tip, i.e., the value of the tool tip radius, can have a great impact on the intensities of forces that occur during the machining process, and thus a direct impact on tool wear during the machining process [83]. With this in mind, part of the research in the field of micro-cutting is focused on the development of a mathematical model for the prediction of forces arising in the cutting zone. One such study is that conducted by G. Bissacco et al. [84] whose presented model took into account the value of the tool tip radius. On the other hand, research conducted by M. Malekian et al. [85], formed a model of force prediction in which, in addition to the value of the tool tip radius, the influence of elastic return of material is incorporated. Research related to the formation of force prediction models in micro-cutting using the finite element method can also be found in the literature [86].

The geometry of the tool tip can also have a significant effect on the geometry of the machined surface. If we are talking about grooving by the method of scratching, different tool geometries lead to a change in the geometry of the formed groove. One such study was conducted by D. Axinte et al. [87] On the other hand, the value of the tool tip radius can have a great influence on the size of the burrs that are formed on the edges of the surface. Decreasing the value of the ratio of the depth of micro-cutting and the value of the tool tip radius, leads to an increase in the value of the raised edge along the trace of micro-cuts [88, 89].

Micro cutting of stone-based materials

Stone-based materials such as granite or marble are difficult to process. Their pronounced brittleness and high hardness, which is also variable within the entire volume, have a great influence on the processing of these materials. The variability of the hardness values of these materials leads to the complexity of choosing the optimal machining parameters, such as depth and cutting speed, which results in machining inefficiencies in the domain of tool consumption and obtaining the desired surface quality. If we take into account the increasing use of stone-based materials, as well as their huge potential for wider application, more intensive research in the field of machinability of these materials becomes justified.

As already mentioned, the main goal in micro-cutting of brittle materials is to obtain a finely machined surface without the presence of traces of material destruction. H. Huang et al [90] found in their research that granite, although brittle in nature, can be processed in a ductile mode, thus obtaining a high-gloss surface. Also, they came to the conclusion that with the increase of plastic deformations in the cutting zone, the roughness of the machined surface decreases. In their research, similar conclusions were reached by the authors [91].

Although there is a large variation in hardness within the entire volume of granite due to its heterogeneous composition, the hardness can additionally differ between different types (varieties) of granite, due to the different minerals from which they are formed. Research has shown that different material properties, such as hardness, can affect the range of ductile mode [76, 92-94]. A model that would take this into account, and which would serve to determine the optimal processing parameters based on the value and variation of the hardness of the material, was presented by J. Xie and J. Tamaki [95]. They came to it on the basis of experiments conducted on ten different types of granite. On the other hand, Y. Li et al. [96] presented a new method of granite processing that increases the durability of tools by having a specially designed tool geometry to influence the friction that occurs during tool-workpiece interactions.

Marble, in addition to granite, is one of the most present stone-based materials with increasing application in industry. Similar to granite, by its nature, marble is a very brittle material with a heterogeneous structure. Depending on the type of minerals that are part of marble, its hardness can vary significantly. In previous research, marble, like most other brittle materials, can be processed in both the brittle fracture mode and the ductile mode [97], however, a small number of studies on this topic have been published so far.

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