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MICROMACHINING OF MICRO AND NANO-STRUCTURED METALS

The microstructure of machined metals change near the tool affected zone. This paper presents some new results concerning mirror-like surface cutting of aluminum and copper. The microstructure of aluminum and copper represents the polycrystalline mild metals with face centered cubic (fcc) crystal lattice. The examination of mirror-like surface by optical microscopy, scanning electron microscopy, electron backscattered diffraction (EBSD) and atomic force microscopy show the grain boundaries and twin boundaries, which separates two domains for different crystal orientation. Young's modulus that depends on orientation can change considerably on these boundaries, consequently the value of elastic deformation of the layer under machined surface. This effect modified the roughness too. Aluminum and copper were cut as "conventional" micro-structured metals used in everyday practice and after so called ECAP process with nano-crystalline structure, for examining effects of crystal size on machinability and surface integrity of machined mirror surfaces. Results of these comparative experiments are discussed in this paper.

Keywords: ultraprecision machining of mirror-like surfaces, copper, aluminum, crystal, micro and nanostructure, dislocations, anisotropy, crystal orientation, surface integrity.

INTRODUCTION

Developments in the engineering industry and the high quality of its products make it necessary the continuous improvement of the manufacturing processes involved and their economic efficiency.

Owing to the increased accuracy and quality of machined parts, investigations of the effect of cutting on the base material structure and its mechanical properties become absolutely necessary. It is well known, that material is plastically deformed under a cut surface and therefore its properties have changed. The effect of the material and its microstructure on the surface finish is especially strong when cutting ultraprecision mirror like surfaces. Mirror surface structural changes, such as grain boundaries on embedded phases, different orientations and anisotropy, may be observed leading to uneven surfaces. Deviations in materials structure always occur on the cut surface and therefore it is absolutely essential to investigate their effect, when machining very fine surfaces [5].
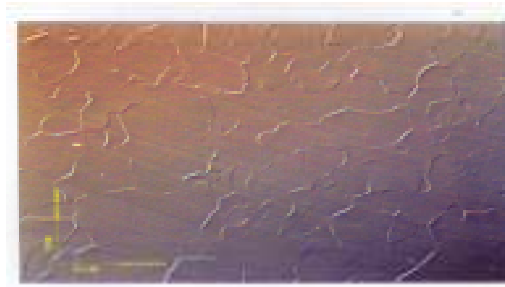
Figure 1 – Microcut surface by microscope (500X)

During ultraprecision cutting, due to very small chip sections, very often single crystals are cut. There is much research on single crystals that demonstrates that the chip undergoes much bigger and inhomogeneous plastic deformation than the cut surface layer, while plastic deformation takes place in some determined layers of the material. (Fig.1)

Machining of micro structured copper and aluminum for analyzing effects of anisotropy, crystal lattice and mechanical behavior of different materials cutting experiments was made. The Al and Cu specimens were fixed on a disk on a dia 160 mm in the chuck of the lathe, so the traces of the tool paths could be considered as parallel straight lines.

When machining mirror like surfaces the bigger the anisotropy of the modulus of elasticity of the material, the greater surface roughness is. However, the surfaces integrity is affected not only by the anisotropy of crystalline structure but also by all the parameters of plastic deformation involved. Therefore, the determination of structural changes occurring during ultra precision machining, together with the increased temperature in the machined surface layer may be useful for estimating the surface integrity of machined component.

The work utilized in cutting is a function of the plastic deformation of the material. Elastic deformation vanishes when the cutting tool moves away and the temperature increase. About 10% of the work spent for plastic deformation results in an increase in dislocations density, while the rest is used in increasing the temperature.

FORMATION OF SURFACE ROUGHNESS IN MICROTURNING AT COPPER

Two important material properties of copper are its cubic face-centered atomic lattice structure, and intense anisotropy. The elastic or Young modulus of copper is changing from E = 66.71 103 N/mm2 to E = 192.33 103 N/mm2 depending on the orientation of crystal planes. The smallest value can be measured in the <100> direction, while the largest value is in the <111> crystallographic direction. The variation of other mechanical material properties,

such as relative strain (ϵ), tensile strength (σ_b) and the modulus of shear elasticity (G), is similar to the Young modulus [3]. These facts are corresponding to single crystals. In case of polycrystalline materials the values above are only relevant inside crystal boundaries, accordingly inside individual crystal. During conventional cutting, the shear, plastic deformed zone is much greater than the average crystal dimensions; hence gliding is taking place over crystal boundaries.
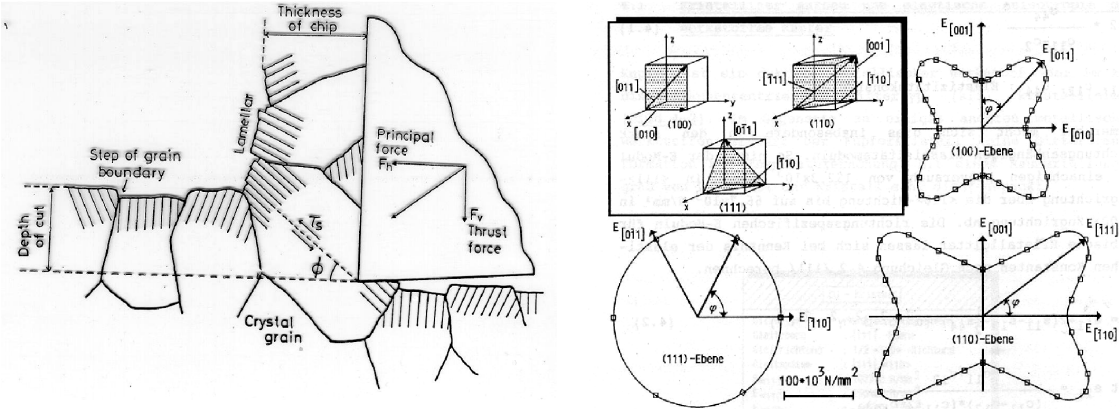

Figure 2 – The anisotropy of the materials
and the spring-back effect (after Moriwaki [1])

In spite of this in micromachining and/or ultraprecision cutting the chip root dimensions are significantly smaller than the average grain size, which means that gliding is taking place inside the crystal boundaries. Since the crystallographic orientations of the grains are different, this anisotropy causes a change in the generated force during the cutting of different grains. After the cutting tool goes past, the grains spring back to different extents due to the elastic deformation. The effect is described on Fig. 2 after Moriwaki [1].

On the basis of the model many sections of the machined surface topography can be explained, however it does not give an explanation to the event that the large roughness peaks often originate in crystal boundaries. Spenrath's [2] explanation for this effect is that due to the stress field before and under the cutting tool dislocations start inside the grain boundaries, which are blocked at the crystal boundaries. The dislocations are piled up at crystal boundaries and increase locally the strength of the material. When the crystal boundary is cut, a larger force is produced, which induces greater elastic deformation, and this increased elastic deformation causes larger local spring back. Most of the effects can be explained with the theory of dislocation migration [4], but it still leaves some questions open. For example roughness peaks cannot be found at all the grain boundaries [6, 7, 8].

238

SURFACE OF COPPER SPECIMENS

On the Fig. 3 etched macroscopic image of original state of the soft copper specimen is shown. In internal parts of its crystallites twins with parallel boundaries could be observed. Twins seen in the domain marked E is shown on Fig. 4 made by EBSD techniques. In the unit triangle of the stereographic pole figure, which is seen on Fig. 5 identically marked poles of different domains (grains or twins) show their surface normals. On the Fig. 6 one can see surfaces of Fig. 4 marked identically, showing clearly that tool, crossing crystal domains with different orientations changes the surface roughness to a less extent. As a result metallographic features become observable without any usual preparation only under effect of Nomarski differential interference contrast mode (N-DIC) of optical microscopy [13, 15].

Figure 3 – Macroscopic image of original state of the annealed copper specimen.
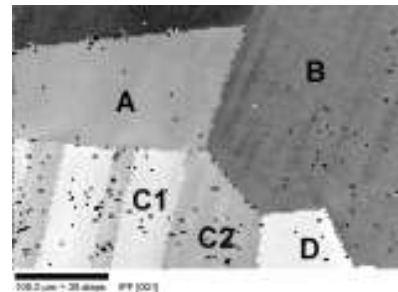

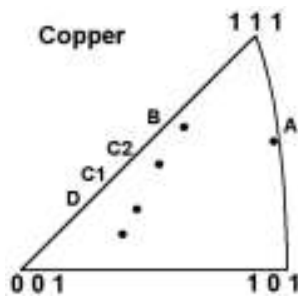Figure 4 – EBSD image quality map of the detail E on the Fig. 2.

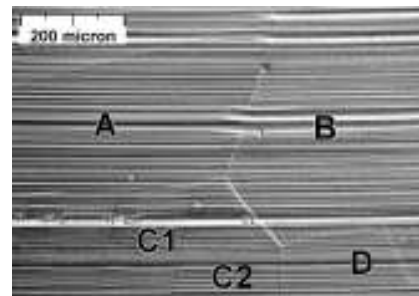Figure 5 – Pole figure showing orientation of crystallites and twins marked on Fig. 3.

Figure 6 – N-DIC image of detail showing on Fig. 3 after ultra precision machining.

Fig. 7a made on mirror-like surface of copper specimen demonstrates, that the trace of the tool changes in every case, when it crosses grain or twin boundary with changing crystallographic properties of domains to be machined. On the Fig. 7a tool, moving from right to left, crosses at first a crystallite, then in the new crystallite it cuts the surface of a twin, making observable its both boundaries. Fig. 7b made by atomic force microscopy (AFM) shows the 3D plot of a grain boundary on mirror cut surface of copper [16].
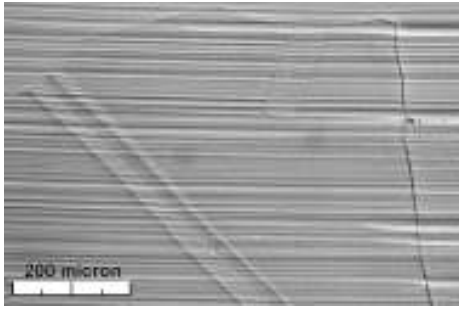
Figure 7a – N-DIC image of twin boundaries and grain boundaries on mirror cut surface
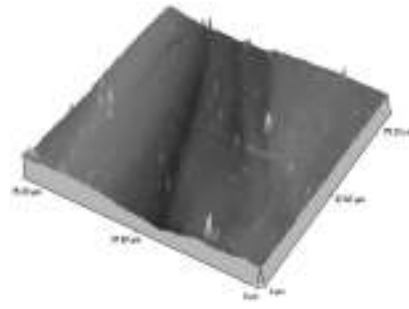

Figure 7b – 3D plot of a grain boundary on mirror cut surface

We get similar results with Al. Size, orientation and moduli E and G have determinative effect on surface integrity during the machining.

EXPERIMENTS WITH NANO-STRUCTURED METALS

The cutting experiments were made with nano-crystallines Al, Cu and Steel. Nano-crystallines structure was achieved as results of high rate of plastic deformation. In this paper authors deal only with experiments on Al. For achieving nano-structure the equal-channel angular pressing method was applied.

Equal-channel angular pressing (ECAP) is a processing method in which a metal is subjected to intense plastic straining through simple shear without any corresponding change in the cross-sectional dimensions of the sample. This procedure may be used to create ultra fine grain sizes in bulk polycrystalline materials.

Equal-channel angular pressing (ECAP) is a processing method in which a metal is subjected to intense plastic straining through simple shear without any corresponding change in the cross-sectional dimensions of the sample. This procedure may be used to create ultra fine grain sizes in bulk polycrystalline materials. The principles of the ECAP process have been examined with reference to the distortions introduced into a sample as it passes through an ECAP die with special attention to the effect of rotating the sample between consecutive passes. Significant distortions of the grain structure occurred when a sample passed through a standard ECAP die, so when a sample is pressed repetitively through the die, it has been recognized that the overall shearing characteristics within the crystalline sample may be changed by a rotation of the sample between the individual passes. The repetitive pressing of the same sample is generally carried out in order to attain very high imposed strains. At the same time there is an opportunity to rotate the sample between consecutive pressings in order to activate different shear planes and directions, thus enhancing the mechanical properties at room temperature by applying different routes [9, 10].

It is well known that plastic deformation induced by conventional forming methods can significantly increase the strength of metals. However, this increase is usually accompanied by a loss of ductility. It has been found recently that materials processed by ECAP after certain number of passes show high ductility along with high strength. Such unusual behaviour of materials, which is in contradiction with 'classic' tendencies to lost ductility with increased strength, needs to be understood deeper. In this paper the effect of different routes of ECAP techniques on the strength and the ductility of an Al-based alloy is investigated. The mechanical behaviour is related to the characteristic features of the nano-crystalline microstructure formed during ECAP deformation [11].

The material used in this study was a commercial Al-Mg-Si alloy (Al 6082). The main components of the alloy are Al (97%), Si (0.7–1.3%), Mg (0.6–1.2%) and Mn (0.4–1%). Before the ECAP deformation, the material was annealed at $420°C$ for 40 minutes. Specimens in this condition were regarded as the as-received material. Cylindrical billets of 15 mm in diameter and 145 mm in length were pressed through the ECAP die with $90°C$ intersecting channels. Four and eight passes were completed by the following routes: BC (rotation of the billet around its longitudinal axis after each pass by $90°C$ clockwise), BA (rotation of the billet around its longitudinal axis after each pass by $90°C$ clockwise and counterclockwise, alternatively) and C (rotation of the billet around its longitudinal axis after each pass by $180°C$, clockwise). The temperature of deformation was 293 K and the displacement rate of the billet was 8 mm/min [12, 14].

It was found that nano-sized microstructure (mean crystallite size ~ 80 nm) with high dislocation density (3×10^{14} m^{-2}) was achieved even after the first pass. The microstructure was refined only slightly during further ECAP passes. At the same time the dislocation density increased with the increase of ECAP deformation up to 4 passes. The dimensionless dislocation arrangement parameter, M, has a value of 4.0 ± 0.4 for the as-received specimen and it decreased to 2.2 ± 0.3 after 8 ECAP passes. This indicates that the dipole character of the dislocation structure became stronger with increasing deformation.

SURFACE INTEGRITY MEASUREMENT

The effect of crystal size and the ECAP process on the surface integrity was investigated by making mirror-like cylindrical and flat surfaces, using turning. An ultra-precision lathe (Csepel UP-1) and Winter mono-crystalline diamond tool were used in these experiments.

The turning process has been applied to every specimen with the same cutting conditions.

The set machining parameters were:

cutting speed (v_c)   78 m/min

feedrate (f)   5 µm/rev

cutting edge radius (r_β)   50 nm.

The sample surfaces, prepared by ultra-precision machining, demonstrated interesting changes. The original surface quality was nearly identical to that after the fourth pass. After eight passes, however, the surface roughness dropped by a factor of five, further reflecting the effect of the structural changes. In turning experiments after eight steps of pressing – under equal cutting conditions – cut surface roughness reduced by a factor of five on average (from $Ra = 55$ to $Ra = 10$).

The results can see on the next table (Table 1).

Table 1 – Forming of surface roughness in function of ECAP number

No. of ECAP	Average surface roughness (Ra, nm)	Surface roughness, (Rz, nm)
0	49,6	283,1
1	54,8	402,9
4	53,3	272,7
8	9,5	70,87

Surface roughness was measured with Atomic Force Microscope (Fig. 8). The results are very interesting and very promising: surface finish of the cut raw part had the same value.
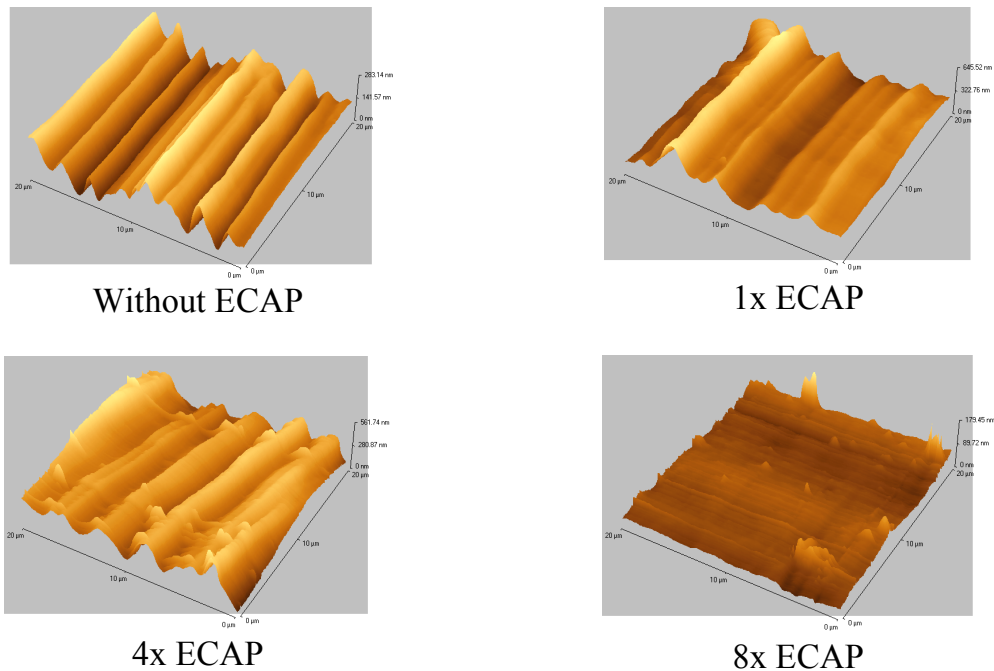
Without ECAP

1x ECAP

4x ECAP

8x ECAP

Figure 8 – Microscopy explosures in function of ECAP number

CONCLUSIONS

For getting mirror like surfaces with nanometer size parameters of surface integrity one have to eliminate the influence of crystal orientation, different moduli of elasticity, anisotropy. The only possibility is to decrease the sizes of crystallines up to 100nm. They should be less, then active edge of cutting tool. In this case the tool edge is crossing many crystallines in one pass (feedrate is several μm), and influences of different crystals neutralize those of each other.

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ТЕХНОЛОГІЧНЕ ЗАБЕЗПЕЧЕННЯ ЯКОСТІ

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THE MANAGEMENT OF SURFACE QUALITY OF METAL WITH NANO AND SUBMICROCRYSTALLINE STRUCTURE DURING MACHINING

Розглянуті особливості поведінки нано- та субмікрокристалічних металів, отриманих методом інтенсивної пластичної деформації, під впливом температурного чинника, виникаючого у процесі механічної обробки заготівок. Представлена послідовність дій для отримання раціональних умов обробки, які забезпечать збереження вихідної структури металу та високу якість поверхневого шару після механічної обробки. Запропоновані раціональні умови обробки для деяких металів з нано та субмікрокристаллічною структурою.

Рассмотрены особенности поведения нано- и субмикрокристаллических металлов, полученных методом интенсивной пластической деформации, под воздействием температурного фактора, возникающего в процессе механической обработки заготовок. Представлена последовательность действий для определения рациональных условий обработки, которые обеспечат сохранение исходной структуры металла и высокое качество поверхностного слоя после механической обработки. предложены рациональные условия обработки для некоторых металлов с нано- и субмикрокристаллической структурой.

The behaviour features of the nano- and submicrocrystalline metals affected by the temperature factor incipient during cutting are considered. The metals are processed by methods of severe plastic deformation. The operations consistency in order to get the rational machining conditions is presented. The rational machining conditions will ensure the conservation of the initial metal structure and high workpiece surface quality after cutting. The rational machining conditions for the same metals with nano- and submicrocrystalline are suggested.

From the broad spectrum of all nanomaterials only bulk nano- and submicrocrystalline metals are considered in this paper. These metals are processed by methods of severe plastic deformation (SPD) [1].

Some research [1-5] has shown that the mechanical characteristics of the nanocrystalline metals essentially differ from macrocrystalline metals. The practical interest is the high strength properties of nanostructure metals, such as strength, microhardness, increased damping capacity etc.

The bulk nanocrystalline and submicrocrystalline metals are used in medical, aircraft and auto engineering industries [1, 6].

The nano- and submicrocrystalline metals, got by SPD, differ in instability structures. The observed grain growing can be explained by high internal tensions. The sources of tension are nonequilibrium of a boundary grain and a crystalline lattice distortion [1]. The temperature of a grain growth beginning (0,2-0,3Tm [7, 8]) in nano- and submicrocrystalline metals is lower than in macrocrystalline metals. Complex structured changes occur with the

development of the processes of the return, recrystallization, growing grain and loss of high physical-mechanical properties in the nanocrystalline metals at heating [1, 9]. The intensity of the recrystallization process, resulted in grain growing, is determined by degree and time of the thermal action.

Usually, manufactured parts are made by means of the cutting.

Cutting is a complex process of plastic deformation. It is accompanied by intensive heat generation with significant stress in zone of the contact "instrument – work material" [10].

The physical state (structure, properties) and surface tension of a part are result of elastic-plastic deformation and local heating in a cutting zone. The heat occurs during plastic deformation and external friction of working surfaces of the cutting tool on the work material. The heat has a great influence on the physical state of the surface.

Large contact area on the front surface of the tool is characterized for fine metals. This leads to the considerable efforts of friction. Small value of a shear gives the increase of cutting speed and temperature in the cutting zone. The temperature in the cutting zone for technically fine nickel, titan and copper are 973, 873 and 573 K respectively [11].

It can be hypothesised that temperature in the cutting zone and time of the temperature influence, will cause the grain growth and reduction of physical-mechanical properties of the nano- and submicrocrystalline metals.

The experimental data have confirmed the influence of the temperature and the time factor on grain growth and change of the physical-mechanical properties of the nano- and submicrocrystalline metals. The change of the physico-mechanical properties results in deterioration of performance of the nano- and submicrocrystalline metals.

The main requirement for the formation of the parts is the preservation of the initial submicrocrystalline or nanocrystalline structure of the workpiece. The properties of the metal shouldn't change under the influence of deformation-thermal phenomena during machining.

The force and temperature are main physic factors influencing changes in the structure of the nano- and submicrocrystalline metals. The role of these factors is necessary to determine to find the rational conditions of machining of the nano- and submicrocrystalline metals.

The operations consistency of surface integrity management of metals with nano- and submicrostructure has been developed.

The consistency of workpiece surface quality consists of the following stages:

1. The workpiece with the known initial grain size is chosen.

2. The maximal temperature in the workpiece, time of influence of this temperature and penetration depth of the maximal temperature is determined. For this purpose the model of calculation of the thermal fields is used. The