CHIP FORMATION IN MILLING OF ULTRAFINE-GRAINED STEELS

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Abstract. *This work quantified statistically the effect of the depth of cut, feed rate and cutting speed on the chip formation and its relation with the specific cutting energy when end milling ultrafine-grained steels. The experimental tests were carried out in a machining center with 11 kW power by using 25 mm diameter end mill with two cemented carbide inserts and Al2O3 coating. Applying Analysis of Variance in a 2^3 factorial design, the results indicated that the increase of cutting speed and feed rate decrease the specific cutting energy by which reduces both the chip microstructure angle and cutting ratio. Depth of cut is not significant. For higher cutting speeds, segmented chips generated by adiabatic shear were found.*

Keywords*: milling; chip formation; ultrafine-grained steel*

1. INTRODUCTION

With the development of machining processes has greatly increased the use of called High-SpeedMachining (HSM) mainly due to major advantages attributed to the process, for example, time savings, lower cutting forces, better heat dissipation, less distortion of the piece, better accuracy, lower levels of mechanical vibration, greater facility in removal and storage of chips and better surface finish, always aiming at productivity growth (CHEVRIERet al., 2003).

The machining with high-speed cutting (HSC) is used industrially for finishing operations, mainly in the manufacturing of dies and molds. The difference between this HSM is that is specifically about the cutting speed, not the process as a whole.

With monitoring the forces, it is possible to calculate the specific cutting energy which is a relationship between cutting power and material removal rate (KING; HAHN, 1986). The specific energy reflects the energy necessary to execute the process.

The geometrical and metallurgical characteristics of the chips are so representative in the performance of the machining process. Really, they show most of the thermal end physical phenomena that occur during machining (SUTTER, 2005). In high-speed cutting, the chip shearing occurs in the primary shearing zone (FLOM; KOMANDURI, 1989).

The segmented chips show greats continuous deformations in narrow bands between the segments which has a little or no deformation. It is a very different process of formation when compared to continuous chipformation (MACHADO et al, 2009).

When studying machining is important to investigate the effect of many variables that make up the phenomenon of shear to better understand the process and indicate the most efficient method.

2. METHODS AND MATERIALS

2.1. Experimental strategy

Looking for associate the effects of milling in the chip formation mechanism, ranged up three cutting parameters, each in two levels, cutting speed, depth of cut, and feed rate. Riding a factorial design (2^3) results in eight cutting conditions, as showed in Tab. 1.

Table 01. Cutting parameters and experimental design used on test

Input variables	**Machining conditions**							
	C1	**C2**	**C3**	**C4***	**C5***	**C6**	**C7**	**C8**
Cutting speed [m/min]	100	100	100	100	600	600	600	600
Depth of cut [mm]	0,5	0,5	3,0	3,0	0,5	0,5	3,0	3,0
Feed per tooth [mm/tooth]	0,05	0,2	0,05	0,2	0,05	0,2	0,05	0,2

*Conventional condition (C4) and HSC (C5)

The experimental design makes possible check the influence of each input variable. The Variance Analysis (ANOVA) was the statistic tool used to check the effect of these variables, for this analysis was necessary hold a replication of the tests.

Two materials were used in tests of milling; they named as “as-received” (CR) and “ultrafine grained” (GUF). The steel supplied by Usiminas Cubatão – S/A, as thick plates, known commercially as COS AR 60, part of the specimens were subjected to a thermomechanical processing to obtain a structure with grain size close to 1,7 µm. The Tab. 2 shows the chemical composition of the material.

Table 2. The chemical specification of material (% in weight)

C	**Mn**	**P**	**S**	**Si**	**Al**	**Cu**	**Cr**	**Ni**	**Nb**	**V**	**Ti**	**Ceq**
0,15	1,49	0,027	0,009	0,27	0,046	0,005	0,276	0,008	0,048	0,044	0,016	0,40

According to company data, the material studied in this work is a low carbon steel with improved properties. It has resilience limit of 630MPa, a yield strength of 530MPa, and elongation of 26%. In the impact test with V notch of 2mm, the average energy absorbed until fracture at a temperature of 0ºC is 176J.

The differences in microstructure can be observed in “Fig. 1” where in (a) has become the material “as-recived” showing a average grain size of ferrite of 10.8µm and (b) the micrograph of the material with ultrafine grains, with average grain size of ferrite of 1,7µm measured by ASTM E 112-95. For images, note the reduction in grain size of the material after thermomechanical treatment.

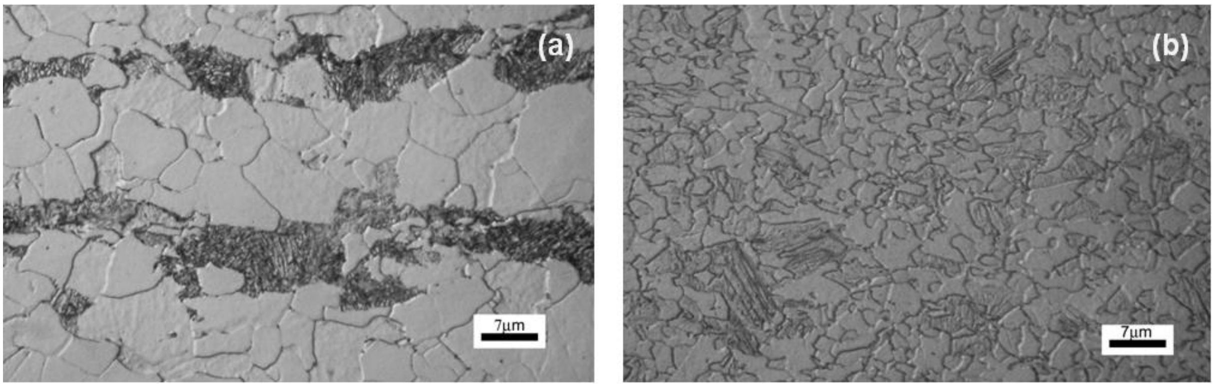

Figure 1. Material micrography (a) “as-received” and (b) ultrafine grains
(Marshall Attack followed of Nital 1%).

The milling test were conducted on a CNC machining center, brand ROMI, Discovery 560 model, with maximum rotate of 7500rpm, 11kW of power an maximum fast forward of 30m/min. The inserts of tungsten carbide and the support of chuck-cutter used in the tests were specified with the aid of SandvickCoromant, manufacturer tools. The inserts coated of $Al2O3$ belong to ISO P15 class, ranging between P5 and P25, wich brings good toughness and high wear resistance. Are appropriate tool for optimized milling operations, whithout refrigeration, on the machining of steels with high rates of material removal and higher cutting speeds.

2.2. The specific cutting energy

To calculate the specific cutting energy was needed to acquire the force data, a piezoelectric dynamometer brand Kistler, model 9257BA, 3 components acquisition, track work in Fx, Fy from -5 to 5 kN and the Fz -5 to 10kN, the natural frequency of 4kHz, stiffness of 100N/µm and a charge amplifier with 3 channels, brand Kistler, model 5233A. For conversion and transmission of analog signals to digital, was used a data card acquisition, brand NationalInstruments and conectors block of the same brand.

The dynamometer was fixed on the machine tool table by clamps and connected to charge amplifier, which was connected to the connector block that plugs into acquisition board, and this is connected to the notebook with software Labview 7.1. The "Fig. 2" presents the details of the fastening system of the dynamometer.

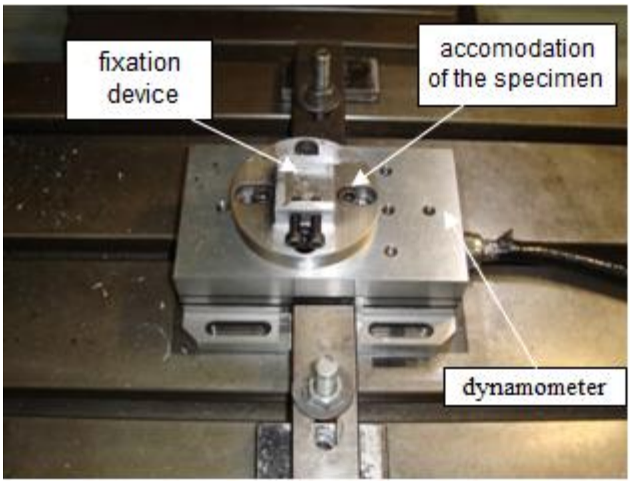

Figure 2. Fixation of the specimen and dynamometer

2.3. Chip Study

The chips generated in machining were collected and cataloged. For this analysis was first necessary embedding into Bakelite as showed in "Fig. 3", each Bakelite sample, group two chips of different machining conditions and your replics. The chips were glued on sheets that formed a support, around is used a square profile to supporting the sanding.

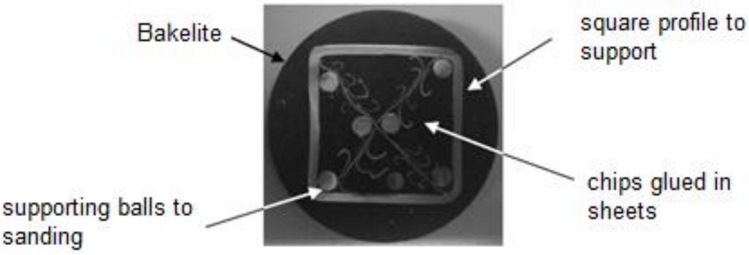

Figure 3. Chips embedded into Bakelite.

The embedded was followed by steps of sanding and polishing to obtain a smooth surface. Then the attack was made with Marshall's reagent and successive attacks of Nital 2%, to obtain a visible microestructure. Then in optical microscope, brand Carl ZeissJena, model Neophot 21, images were made for qualitative analysis. Through these images in a process with aid of imaging software and CAD software was possible to obtain the angle of deformation od the microstructure as shown in "Fig. 4"

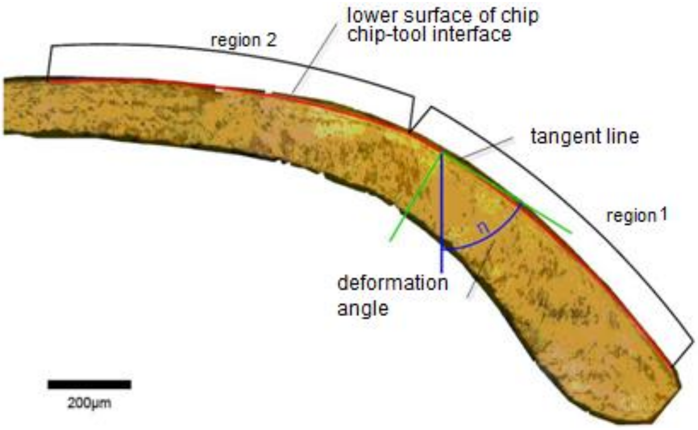

Figure 4. Representation of measurement mode of microstructure angle

2.4. Roughness

The surface of the specimens was valuated using a digital roughness meter's brand Mitutoyo, model SJ-201P, with tip radius of 5 µm. The objective was to analyze the surface condition and relate them to the cutting parameters. The parameter adopted was Ra, which represents the arithmetic mean of amplitudes between the peaks and valleys over a center line.

3. RESULTS AND DISCUSSION

3.1. The specific cutting energy

In calculating the specific cutting energy, which is a variable that represents the efficiency of the process and is subject to the influence of cutting conditions, workpiece material and tool. Table 3 shows the ANOVA table for specific cutting energy, with the data obtained in the tests.

Table 3. ANOVA table for specific cutting energy

Control factor	Liberty degrees	Sum of Squares	Mean square	F Test	P value
Material*	1	195,62	195,62	117,31	0,000
Cutting speed*	1	45,23	45,23	27,13	0,000
Cutting depth	1	4,60	4,60	2,76	0,100
Feed rate*	1	396,81	396,81	237,97	0,000
Error	91	151,74	1,67		
Total	95	794,00			

* Signification factor

Analyzing the results, it is observed that only the depth of cut had no statistically sifnificant influence on specific cutting energy, for this to happen the P value should be less than 0.05. Other factors such as workpiece material, cutting speed, and feed rate were influential in the specific energy. These data were made comparative graphs, shown in "Fig. 5".

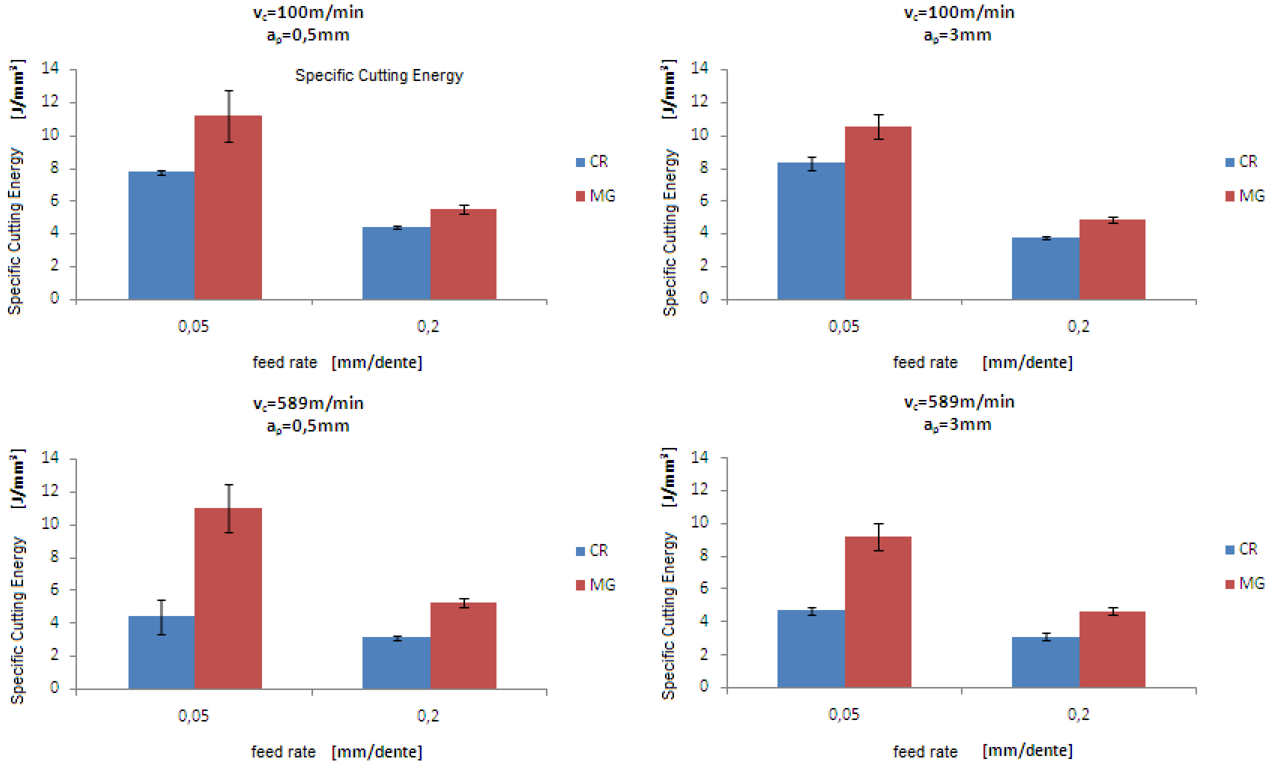

Figure 5. Specific Cutting Energy for any cutting conditions

The increase in cutting speed caused an average reduction of 34% in specific cutting energy for the material provided CR. As for the material GUF, high cutting speed, considering the confidence intervals of 95% resulted in lower specific cutting energy.

The increase in feed rate results in decrease of specific cutting energy, this being the most significant parameter. Results showed an average reduction of 41% for CR and 52% for the GUF. The depth of machining already evidenced by the ANOVA no represents visual changes in specific energy for the two microstructural conditions of the material.

Analyzing the behavior of the material of the piece, the condition CR had lower specific energies that material GF, reaching an average reduction of 35%. We also mention that the reduction of specific cutting energy in different microstructural conditions of the play is enhanced when the cutting occurs at higher cutting speeds.

3.2. Deformation angle of microstucture

With the measures the angle of deformation of the chip microstructure was generated in the table ANOVA shown in Tab. 4

Table 4. ANOVA table of microstructure deformation angle.

Control factor	Liberty degrees	Sum of Squares	Mean square	F Test	P value
Material*	1	76,23	76,23	0,81	0,375
Cutting speed*	1	1052,14	1052,14	11,22	0,002
Cutting depth	1	47,36	47,36	0,50	0,483
Feed rate*	1	769,01	769,01	8,20	0,008
Error	27	2532,85	93,81		
Total	31	4477,59			

* Signification factor

Both the metallurgical condition of the material as depth of cut did not show significance levels to assert that influence the process. Figure 6 shows how the control factors acted in the variation of the microstructure angle in the CR samples. As observed, the increase in cutting speed and feed rate reduces the value of the angle of the microstructure, while the depth of machining and metallurgical condition of the material, not statistically relevant, slightly varied around the mean.

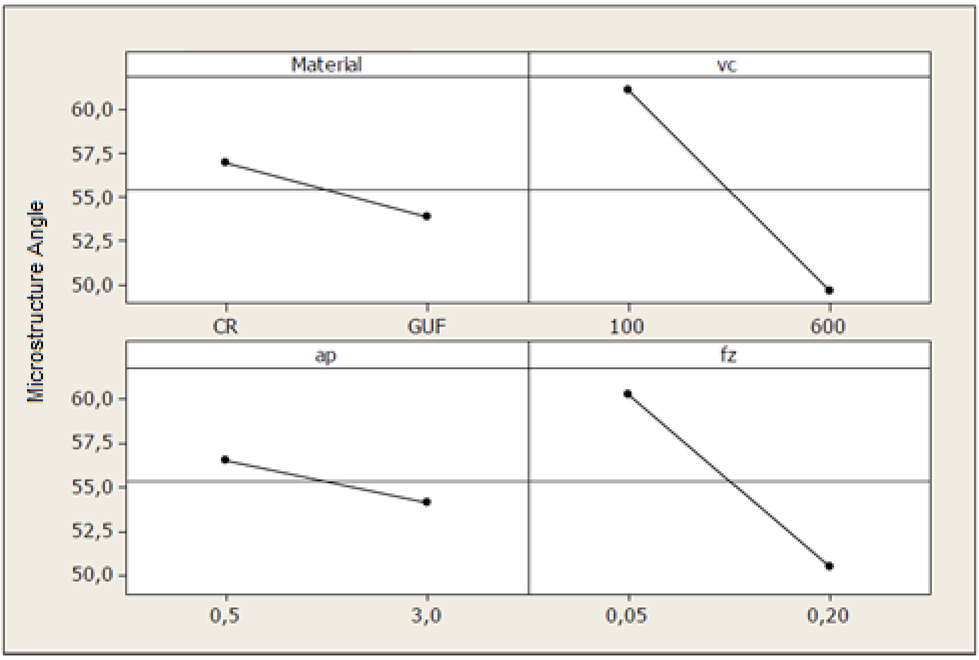

Figure 6. Graphs of deformation microestructure angle variation

Although the material does not significantly influence, the fact is that hardness is related to the type of chip, and also promotes its breaking mechanism, contributing to a better finish.

In fact, the reduction in angle represents a consequence triggered by the increase of cutting speed and/or advancement of the tool, forming the angle of shear increases (the biggest change of momentum in the plane of shear) and the chip thickness and grade decrease in repression, minimizing strain on the primary shear zone and improving the machinability of the material average.

3.3. Roughness

The control of roughness is made to verify the surface finishing of the workpiece. In the same way as other variables of the data mean roughness (Ra) were analyzed statically as shown in Tab. 5.

Table 5. ANOVA table of roughness

Control factor	Liberty degrees	Sum of Squares	Mean square	F Test	P value
Material*	1	1,1590	1,1590	13,49	0,001
Cutting speed*	1	2,2208	2,2208	25,86	0,000
Cutting depth	1	0,1755	0,1755	2,04	0,164
Feed rate*	1	0,6874	0,6874	8,00	0,009
Error	27	2,3190	0,0859		
Total	31	6,5617			

* Signification factor

Only the depth of cut did not affect the results statistically. In “Fig. 7” we can see graphically the influence of factors.

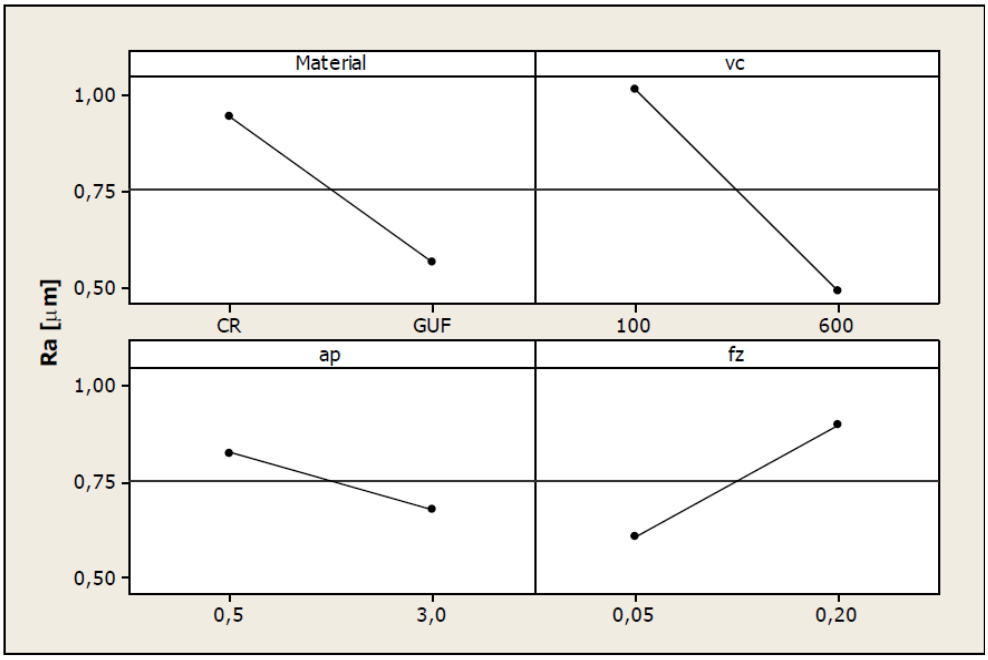

Figure 7. Graphs of mean roughness (Ra)

In this case we have the material being machined as a significant factor in the results. This is because the suface quality is related to the type of chip formed during the cutting process, influencing the specific cutting energy for it to happen.

As expected with increasing advances have increased the average roughness and consequently the surface finish is damaged. The highest hardness of the material with ultrafine grains allowed greater resistance to deformation causing the material to present a smooth finish. As the cutting speed, it is observed that the factor which influences the surface roughness, which can be explained by the change in the dynamics of what happens when we cut to high velocities associated with the material properties.

The increasing of the cutting speed may have caused physically increasing the angle of shear in the primary shear zone and reduced thickness of the chip, which generates lower level of repression and improved chip formation, also reducing machining efforts.

3.4. Qualitative study of Chip

Using the images of chips, optical microscopy, we understand the dynamics of training to justify the results of both the energy and the finish. In "Fig. 8" have images for chips of the material "as received".

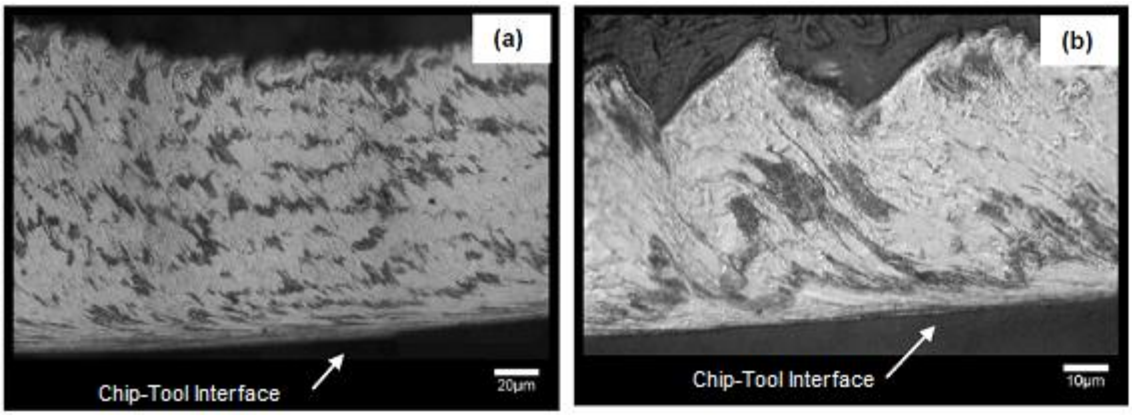

Figure 8. Chip images CR - (a) condition C4 (b) condition C5

Using the images we can see that the deformation is continuous, and all along the chip. Provide C5, which has a higher cutting speed, have a tendency to form shear chip.

In the "Fig. 9" have generate images of the chips with ultra-fine grain.

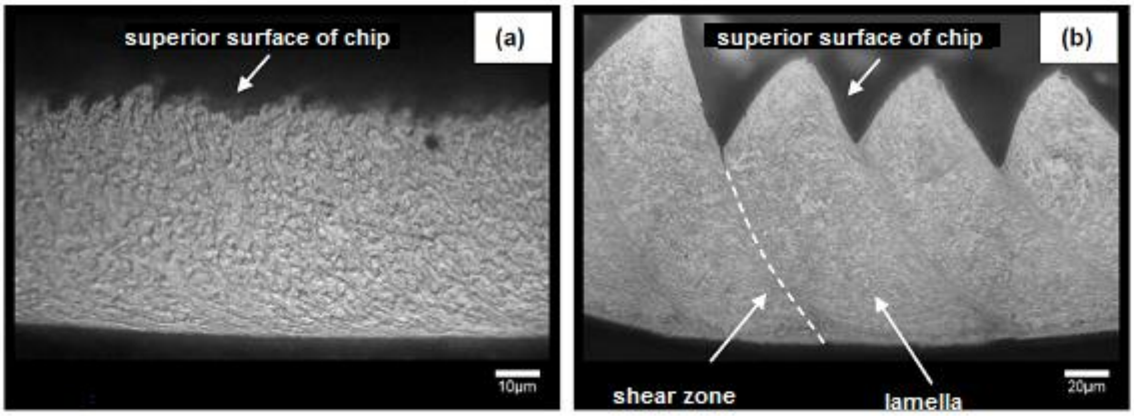

Figure 9. Chip Images GUF – (a) condition C1 (b) condition C6

The Figure 9 clearly show the shear concentrated in a narrow band, forming lamellae which in its interior are not distorted, this lineup featuring the chip type of shear. We note that among the conditions, the main factor that influenced this formation was the cutting speed.

With regard to form, considering ISO 3685: 1993 (E), the chips had to be fragmented for the conditions C1, C2, C5 and C6 and bowed to the conditions C3, C4, C7 and C8. The relationship between the forms is on the cutting depth, which is higher in second case.

According to the parameters investigated, we note that the factors that most influence the dynamics of the cut are the cutting speed and feed rate. The microstructure of the material played an important role in specific energy and surface roughness. The depth of cut is related to the shape of the chip.

The adiabatic shear justifies the decrease in specific cutting energy, because with the energy concentrated between the lamellae yield value decreases. With increasing speed is to decrease the angle of the microstructure, resulting in lower distortion. Moreover, with less strain have a lower roughness.

4.CONCLUSION

After analyzing the results obtained through the parameters adopted, it is concluded that:

- Increases the speed and feed rate decrease the specific energy of cutting, and the angle of deformation microstructure;
- Increasing the cutting speed decreases the average roughness (Ra), but with increasing advance roughness increases;
- The decrease in grain size leads to an increase in specific energy and reducing the roughness, because with the increase of hardness is difficult to plastic deformation on the surface;
- The depth of cut does not influence those parameters, but is related to the shape of the chip;
- The decrease in specific cutting energy is related to dynamic adiabatic shear, found conditions for high speed, along with the reduction of friction, and reducing the angle of the microstructure;
- Analyzing only the points raised in this paper, the condition C7 is presented as the best machining condition, because the high cutting speed decreased the specific cutting energy, the smallest advance improved the finish, and greater depth of compensated machining productivity over the slow progress since it did not affect other parameters.

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