A STUDY OF THE CUTTING FORCE AND POWER IN THE MACHINING OF 6262-T6 AND 7075-T6 ALUMINUM ALLOYS

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Abstract. *Because of theirs excellent characteristics – especially – the high strength to weight ratio, the application of aluminum alloys has grown considerably in recent years. Part machined can result in the generation of up to 80% of volume of chip from the raw material. Thus the machined parts are only a small fraction of the raw material. Understanding the effects of mechanical properties and cutting conditions on the machining force components and on cutting power represent an initiative to enhance the knowledge on aluminum alloy machinability. The machining force components (Fc, Ff and Fp) can be related to the energy consumed to form the chip and to the tool condition (or tool wear). The machining forces in the machining of aluminum alloys is strongly influenced by the strength of the work material at the shear planes as well as the area of these shear planes. Based on this assumptions, there are many factors that can reduce cutting force and power like the presence of free cutting chemical elements into the material, high cutting speeds, low feed rates and depth of cuts, high rake angles and low friction at the chip-tool interface. Comparing to steels, aluminum alloys present low cutting forces and the cutting speed is always the limiting factor for the power required to machine them. In the present work the effect of the mechanical properties and cutting conditions on the cutting (Fc), feed (Ff) and passive (Fp) forces and on the cutting power were studied. The machining force components were measured by means of a piezoeletric dynamometer whereas cutting power by means of Hall effect sensors whose voltage signals were acquired using a data acquisition board – during the turning of the 6262-T6 and 7075-T6 aluminum alloys. These alloys were chosen since they allow a broad spectrum of mechanical strength and hardness to be investigated. Uncoated carbide insert was used as the cutting tools. The cutting conditions were established by means of factorial design of experiment* 2^k *whose factor's levels were: the alloy (6262-T6, 7075-T6) with different mechanical strength levels, cutting speed- Vc (200 m/min, 600 m/min), feed rate- f (0,20 mm/rot; 0,35 mm/rot), depth of cut - doc (1 mm, 4 mm) and lubri-cooling condition (dry, wet). The results were evaluated using ANOVA with significance level of 5%. The results showed that the mechanical properties of the work materials alone or interacting with other factors had significant effects on the machining force components and cutting power.*

Keywords*: machining force, cutting power, machinability, turning, aluminum alloys*

1. INTRODUCTION

Cutting forces in the machining of aluminum alloys are usually low compared to those of ferrous alloys due to their lower mechanical strength, which may generate 70% lower specific cutting pressures than in the machining of steels (Jhone, 1994). However, this difference is not the same among aluminum alloys and depends on their chemical composition and physical properties.

Any thermal or mechanical treatment or even the addition of chemical elements that increase the hardness and mechanical strength of an aluminum alloy reduce the chip-tool contact area and may thus reduce the machining forces (Chambers, 1996; Fang and Wu, 2005; Trent and Wright, 2000). This reduction will, of course, be conditioned to the balance of the effects of the increase in mechanical strength and the reduction in contact area. In some aluminum alloys, hard particles in proportions of up to 15% vol. and aging processes, provided the latter do not cause coalescence of the precipitates, may reduce cutting forces by at least 10% (Chambers, 1996; Demir and Gündüz, 2009). Increasing the cutting speed normally reduces the machining forces, regardless of the strength of the aluminum alloy (Demir and Gündüz, 2009; Fuh and Chang, 1997; Manna and Bhattacharyya, 2003), since the shear stress in the primary shear zone and in the flow zone at the secondary shear region decreases with increasing cutting speed because of the increase in temperature they cause (Kilic and Raman, 2007; Machado *et al.*, 2009; Zaghbani and Songmene, 2009). Although high cutting speeds contribute to reduce machining forces, in high speed cutting (HSC) an excessive increase in deformation rates may increase the machining forces (Hamade and Ismail, 2005; Yousefi and Ichida, 2000).

Other situations that may lead to augmented machining forces with increasing cutting speeds are excessive flank wear due to the presence of hard particles (Kannan and Kishawy, 2008). Agreeing to what was seen by Lahres *et al.*

(1997) during the dry milling of the AlSi10Mg casting alloy when sticking of the workpiece material to the tool's cutting surface and considerable amount of wear was observed. However, this problem may be mitigated by the application of minimum quantity lubrication or oil-jet lubrication (Sreejith, 2008).

Increasing the feed rate and/or depth of cut increases the areas of the primary and secondary shear planes, hindering the shearing of the material and increasing the machining forces (Fuh and Chang, 1997; Manna and Bhattacharyya, 2003; Ng *et al*., 2006). Even so, the stresses on the secondary shear plane may be about 30% lower than those on the primary shear plane, since higher temperatures occur here (Zaghbani and Songmene, 2009).

The tool's geometry, particularly its rake angle and nose radius, as well as the geometric changes caused by wear and by built-up edges (BUE), strongly influence the machining forces of aluminum alloys. An increase in the rake angle, whether through the fabrication process or the presence of a BUE, reduces chip-tool contact in the interface region, which in turn reduces the machining forces (Saglam, Unsacar and Yaldiz, 2006). Shankar *et al*. (2005) reported signs of strain hardening in the interface region with reduction of the rake angle during the machining of 6061-T6 aluminum alloy, which may be the cause of the increase in cutting resistance in response to a diminishing rake angle.

Cutting edges with large radius generate small rake angles at the beginning of cutting – at which moment the cutting forces increase (Roy *et al*., 2009). Flank wear can generate excessive machining forces, as reported by Tang *et al*. (2009) during the milling of aluminum alloy 7050-T7451, since flank wear increases the workpiece-tool contact area.

When machining aluminum alloy, flank wear can be reduced, surface finish improved and machining forces minimized by improving the sharpening technique of cutting edges (Castro *et al*., 2008), or by reducing the surface roughness of the diamond coating (CVD: chemical vapour deposition) tools after polishing (Arumugam, Malshe and Batzer, 2006). Coated or solid diamond cutting tools, due to their high hardness and low chemical affinity for aluminum and hence low adhesiveness, contribute to reduce machining forces, according to the results reported by Roy *et al*. (2009) during the machining of pure aluminum with several types of tool materials: (1) As received, (2) TiC (titanium carbide) CVD, (3) TiN CVD; (4) Al_2O_3 (aluminum oxide) CVD, (5) AlON (aluminum oxynitride), (6) TiB_2 (titanium diboride) PVD (physical vapour deposition) and (7) Diamond HFCVD (hot filament CVD).

The cutting forces when machining aluminum alloys are about one third of those when machining steel; conversely, the energy required is much higher due to the need to operate at extremely high cutting speeds (Jhone, 1994). However, the specific cutting energy is very low because large volumes of material are removed due to the high feed rates and cutting speeds employed in order to achieve higher productivity (Calatoru *et al*., 2008; Hamade and Ismail, 2005). Rao and Shin (2001) confirmed these results during high-speed face-milling of 7075-T6 aluminum alloy.

The specific cutting energy tends to increase as the hardness and mechanical strength of machined materials increases and tends to decrease as the feed rate and cutting speed increase, since the former increases the material removal rate while the latter decreases the cutting force. This behavior was confirmed by Ng *et al.* (2006) in the orthogonal cutting of 7075-T6 aluminum alloy.

The cutting power depends on the loads on the shear planes, which in turn depend on the mechanical strength and on the presence of free cutting elements in the alloys, as well as on the cutting conditions employed to machine them (Machado *et al*., 2009).

Increasing the cutting speed – provided it promotes sufficient softening of the alloy and prevents sticking in the cutting region – the rake angle and the hardness up to a given value, as well as adequate lubrication, tend to reduce the cutting power. Oil-jet cooling or even the presence of free-cutting elements such as Pb (lead), Bi (bismuth), In (indium) or Sn (tin) in proportions of 0.10 to 1.0% wt., combined with cutting speeds in aluminum alloy drilling, can contribute to significantly reduce the power since they promote lower adhesiveness and facilitate chip removal (Dasch *et al.*, 2009).

Large rake angle, cut surface with low coefficient of friction and presence of free-cutting elements, inhibit the excessive rise temperature, since they facilitate the flow of the chip over the rake surface, which reduces the loads needed to deform the chip (Fukui *et al*., 2004; Mills and Redford,1983; Trent and Wright, 2000;). Free cutting elements, such as, lead, bismuth, tin or antimony in contents up to 5%, embrittle the chip, because they are present in the aluminum in the form of insoluble fine globules that increase the stress in the matrix itself when merging in high temperatures, due to high cutting speed (Dasch *et al*., 2009).

The cutting power tends to increase along with increased feed rates and the machined length, since the machining forces tend to increase in both situations – in the latter due to the increase in tool wear. This situation was found by Braga *et al*. (2002) when drilling aluminum alloy with 7% wt. Si.

The aim of the present work is to study the influence of the mechanical property of the work material (hardness, tensile strength and elongation) and cutting conditions [feed rate (f), cutting speed (Vc) and depth of cut (doc)] on the cutting force and cutting power when machining aluminum alloys.

2. EXPERIMENTAL PROCEDURE

2.1. Materials for testing

The extruded bars (Ø 101 mm x 2000 mm) of aluminum alloys 6262-T6 (solution heat treated and artificially aged) and 7075-T6 (Alcoa, 2010) were used for the machining experiments. Table 1 presents the chemical composition of these alloys. The first is mainly used in the screw machine products, photocamera parts, nuts, coupling, marine fittings, decorative hardware, fitting appliances, hinge pins, oil fine fittings, valve and valve parts (Aalco, 2010). The second is maily applied in the aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, gears, keys, aircraft, aerospace and defense applications; bike frames, all terrain vehicle (ATV) and sprockets (ASM Inc., 2010).

Table 1. Chemical composition (wt%) of the aluminum alloys 7075-T6 e 6262-T6 (Aalco, 2010; ASM Inc., 2010).

Designation	Cu	Fe	Mn	Mg	Cr	Si	Zn	Pb	Bi	Ti
7075-T6	1.2-2.0	< 0.5	<0.30.	2.1-2.9	0.18-0.28	<0.4	5.1-6.1	-----	-----	<0.2
6262-T6	0.15-0.40	<0.7	<0.15	0.8-1.2	0.4-0.14	0.4 -0.8	< 0.25	0.4-0.7	0.4-0.7	<0.15

2.2. Microstructural analsys and hardness and tensile tests of 6262-T6 and 7075-T6 aluminum alloys

The microstructural analysis was made in the cross section of the samples (10 x 15 mm x 45 mm), taken from the cylindrical bar of the aluminum alloys. The section were ground (600 to 1200 SiC), polished with chromium oxide and diamond paste (3μm) until they become reflexive. After polishing the 6262-T6 aluminum alloy was etched with a chemical solution of 100 ml of distilled H_2O + 4 g of permanganate of potassium + 1 g of hydroxide of sodium (Weck); whereas the 7075-T6 aluminum alloy was etched with a chemical solution of 2 ml of HF + 3 ml of HCL + 5 ml of HNO_3 + 190 ml of H_2O. Then the etched microstructure were analysed in an optical microscope.

The hardness measurement was done in the cross section of the samples (Ø 101 x 10 mm), in accordance with the NBR NM ISO 6507 -1: 2008 - Vickers hardness standard. A universal hardness meter (Wolpert) with a load of 10 kg was used. Twenty indentations in different regions of the transversal section of the aluminum alloy samples were made. Figure 1 presents the mean hardness of the aluminum alloys with a reliability of 95%.

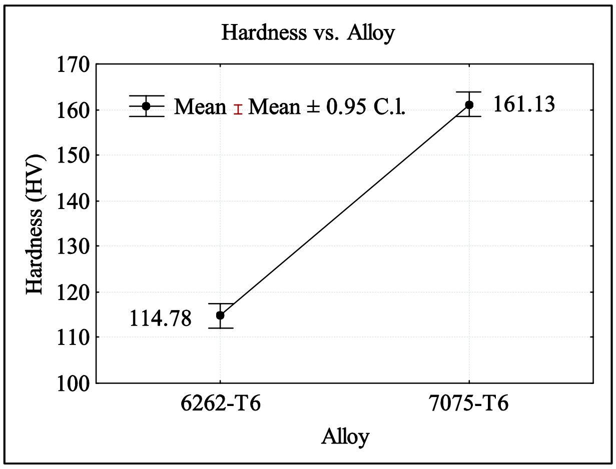

Figure 1. Mean hardness of aluminum alloys

Following recommendations of the NBR 6152 (2002) standard, the tensile tests aimed to determine the mean value of the ultimate tensile strength (*Rm*) and elongation after rupture (*A*) of 04 samples of each aluminum alloys. The tests were performed in a computed tensile testing machine MTS 810 (Material Test System) managed by a workstation MTS TestStarIIs. A strain rate of 2 mm.min^{-1} was used. Figure 2 shows the strength and elongation of the two alloys.

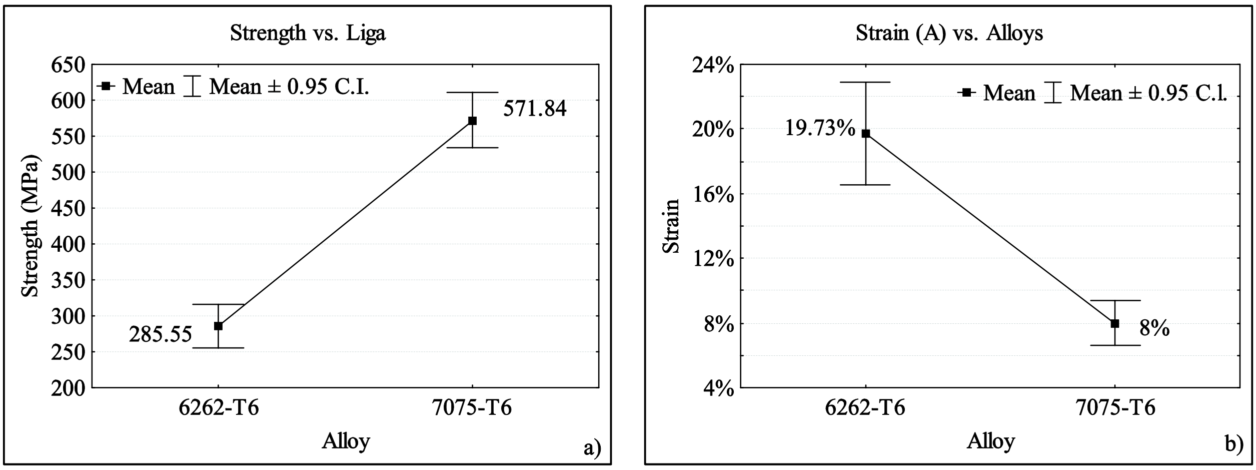

Figure 2. a) Ultimate tensile strength and b) Elongation of the 6262-T6 and 7075-T6 aluminum alloys

2.3. Machinery and equipment

The machine tests were carried out on the CNC lathe (Multiplic 35D manufactured by Industrias Romi S.A.) with 11 kW of power and rotating speed ranging from 3 to 3000 rpm (ROMI, 2010). In the wet cutting condition the cutting fluid (Vasco 1000 from Blaser Swisslube – 6% concentration) was applied using the pumping system of the machine-tool with a flow rate of 360 l/h.. The fluid concentration was frequently checked with an Atago refractometer. The Vasco 1000 is a cutting fluid of high performance with 45% of vegetable oil, 0% of mineral oil, 0.1% of H_2O, density of 950 kg/m^3 (20 °C), viscosity of 56 mm^2/s (40 °C) and flash point of 180 °C.

An ISO STGCR2020K16Z toolholder and TCGT16T308-AZ HTi10, WC-Co uncoated and polished cemented carbide inserts manufactured by Mitsubshi, were used. The inserts have nose radius of 0.8 mm and when one of them is mounted on the toolholder a rake angle of 15°, clearance angle of 7° and approach angle of 90° are resulted.

The machining force components were measured by a tridimensional piezoelectric dynamometer (Kistler 9265B) and charge amplifier (Kistler 5019B). The system was previously and properly calibrated.

The cutting power was monitored using Hall sensors - three current signal conditioner (CSCi), three voltage signal conditioner (VSCi) linked respectively to the three electrical phases that feed the main electric motor of the lathe, HAS 50S (manufactured by LEM)current signal transducers and LV25-P (LEM) transducers. The system was properly calibrated using a voltage/current source MCE 1310 and a digital oscilloscope - Tektronix TDS 2022B.

During the cutting process the force, Voltage and current signals were simultaneously acquired using a data acquisition board (NI USB 6251); a notebook Dell core 2 duo 1.8G Hz/ 4G RAM with the LabView 9.0 software – with a rate of data acquisition of 6 kHz during a period of 5 s.

2.4. Factorial analysis

A full factorial design 2^5 was used with the following input variables and respective levels [low (-1) and high (+1)], in the DOE: i)- Alloy (6262-T6, 7075-T6), ii)- Vc (200 m/min, 600 m/min), iii)- f (0.20 mm/rot, 0.35 mm/rot), iv)- doc (1.0 mm, 4.0 mm) and v)- lubri-cooling system (dry, wet). The combination of these levels generated 32 combinations of tests. Each test was repeated twice. Analysis of variance was done and when the p-value was lower than 5% (0.05) the variable were considered with significant effect on the force and/or power.

3. RESULTS AND DISCUSSION

3.1. Microstrutural analysis

Figures 3a and 3b present the microstructure of the 6262-T6 and 7075-T6 aluminum alloys, respectively. The microstructure of the first is characterized by the presence of dark compounds (identified by the dotted lines) that can be the Bi and Pb. These soft elements are present only in this alloy, as shown in Tab. 1. The microstructure of the second alloy, although with the same thermal treatment of the 6262 alloy (T6) it presents smaller grain sizes. This corroborates with the higher hardness (Fig. 1), higher mechanical resistance (Fig. 2a) and lower elongation (Fig. 2b) of this alloy.

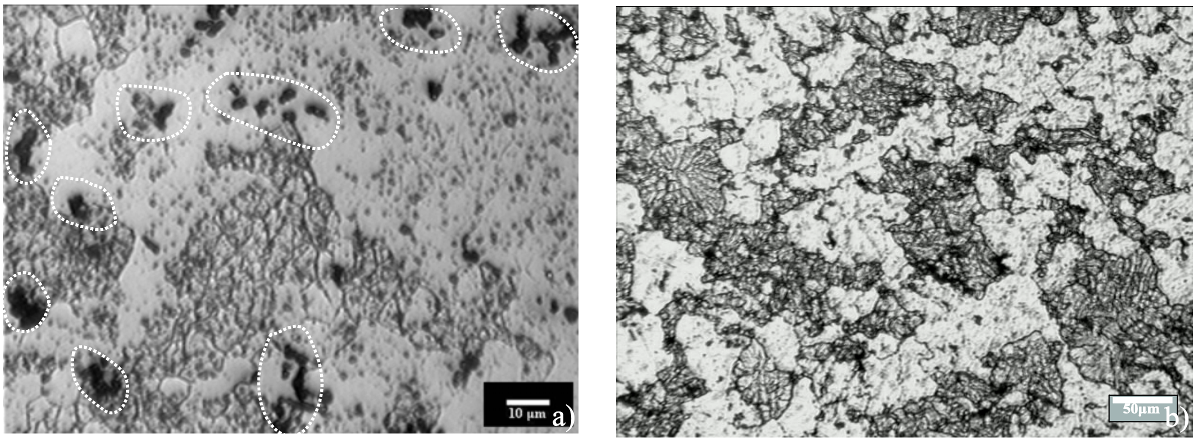

Figure 3. a) Microstructure of the 6262-T6 aluminum alloy: b) Microstructure of the alloy 7075-T6 aluminum

3.2. ANOVA of force components and cutting power

The result of the ANOVA is presented in Tab. 3 (dark mark). It shows that the source of variation with significant effect on the feed force (Ff) were: Alloy, Vc, doc, (Alloy vs. Vc), (Alloy vs. doc), (Vc vs. doc), (Vc vs. f) and (doc vs. f). On the passive force (Fp) were: Alloy, Vc, doc, f, Lub, (Alloy vs. Vc), (Alloy vs. doc), (Alloy vs. f) and (ap vs. f) and on the cutting force (Fc): Alloy, doc, f, (Alloy vs. doc), (Vc vs. f) and (doc vs. f). On Ne: Alloy, Vc, doc, f, (Vc vs. doc), (Vc vs. Lub) and (doc vs f). In Tab. 2 NS represents source of variation no significant for respectively response.

Although Tab. 2 show significant source of variation for feed force (Ff) and passive force (Fp). The cutting force is the main responsable by power consumed during cutting process. Therefore more attention will be given to fisic behavior of cutting force (Fc) and power cutting (Ne) and the relation between them.

Table 2. ANOVA result.

	Ff: $R^2 \sim 0.98$		Fp: $R^2 \sim 0.99$		Fc: $R^2 \sim 0.98$		Ne: $R^2 \sim 0.98$	
	Effect	p-level	Effect	p-level	Effect	p-level	Effect	p-level
Mean/Interc.	70.39	$<10^{-3}$	-5.43	<0.01	360.84	<0.01	3471.93	<0.01
(1)Alloy	38.55	$<10^{-3}$	-2.61	<0.01	75.60	<0.01	448.35	0.04
(2)Vc	-10.71	$<10^{-3}$	-3.06	<0.01	NS	NS	1759.63	<0.01
(3)doc	64.18	$<10^{-3}$	-15.80	<0.01	280.30	<0.01	2192.32	<0.01
(4)f	NS(1)	NS	-8.13	<0.01	123.30	<0.01	634.72	<0.01
(5)Lub	NS	NS	-3.26	<0.01	NS	NS	NS	NS
1 by 2	-4.19	0.09	-1.56	0.05	NS	NS	NS	NS
1 by 3	19.22	$<10^{-3}$	1.60	0.04	26.89	0.008	NS	NS
1 by 4	NS	NS	-0.98	0.02	NS	NS	NS	NS
2 by 3	-7.43	$<10^{-2}$	NS	NS	NS	NS	1224.72	<0.01
2 by 4	-7.13	$<10^{-3}$	NS	NS	-17.56	0.07	NS	NS
3 by 4	4.43	0.07	-5.40	<0.01	82.00	<0.01	NS	NS
2 by 5	NS	NS	NS	NS	NS	NS	-214.77	0.06
3 by 4	NS	NS	NS	NS	NS	NS	617.00	<0.01

(1)NS: Not Significant

3.3. Physical behavior of the cutting force

Figure 4a clearly shows that higher feed rate (f) and depth of cut (doc) promote higher cutting force (Fc); and when machining with the high levels of the feed rate (f) and depth of cut (doc), the cutting force increases more pronounced since this situation generates large primary shear planes and high chip-tool contact area (Fuh and Chang, 1997; Manna and Bhattacharyya, 2003; Ng *et al*., 2006).

Figures 4a e 4b show that the comparison between these two alloys the hardness is a property that prevails over the ductility, where the harder alloy (7075-T6) gave higher cutting force than the more ductile 6262-T6. Previous work of Mario *et al.* (2011) showed the ductility prevailing on hardness during machining of 1350-0 and 7075-T6 aluminum alloy. The presence of the free-cutting elements Pb and Bi in the latter (6262-T6) at the amount of 0.4 to 0.7% (Tab. 1) provides good lubricant action at the chip-tool interface (Dasch *et al*., 2009; Fukui *et al*., 2004; Mills and Redford,1983; Trent; Wright, 2000) and this has resulted in more effective than the reduction of the chip-tool contact caused by the harder 7075-T6 aluminum alloy (Chambers, 1996; Fang and Wu, 2005; Trent and Wright, 2000). It is observed that the cutting force reduction arising from the action of the free-cutting elements is more pronounced at the high levels of the cutting speed (Vc) and the feed rate (f), since in this condition – the cutting speed increases the temperature and reduces the shear stress in the shear planes (Kilic and Raman, 2007; Machado *et al.*, 2009; Zaghbani and Songmene, 2009) and improves the cutting free elements action – they usually have an optimum temperature to be more effective (Dasch *et al*., 2009), and this seems to inhibit the feed action on augmenting the cutting force (Fc).

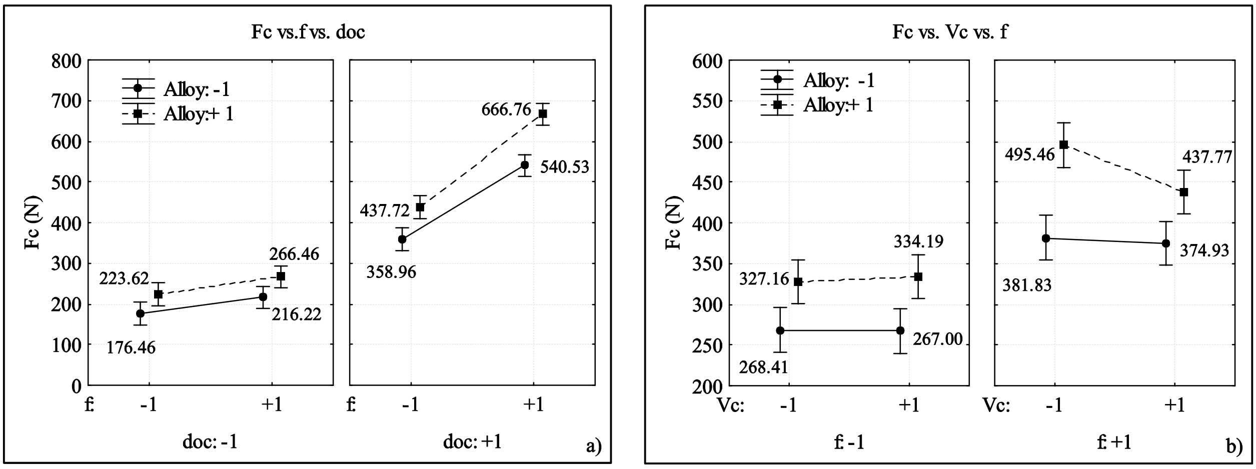

Figure 4. a) Influence of f and doc on the Fc; b) Influence of Vc and f on the Fc

3.4. Physical behavior of cutting power

The cutting Power (Ne) can be calculated by the product of the cutting force (Fc) and the cutting speed (Vc) (Eq. 1), therefore any fact that affect these two parameters will change the power consumption

$$N_e(F_c, V_c) = F_c V_c \tag{1}$$

Figures 5a and 5c show that when increasing the cutting speed (Vc) the cutting power (Ne) also increases, since the effect of the second term of Equation 1 prevails over the first term – where the higher cutting speed generally generates lower cutting forces (see Fig. 4b). The 6262-T6 alloy with the free-cutting elements is cut with lower power than the 7075-T6 alloy because it present lower cutting force as already discussed.

Figure 5a and 5b show that an increment on the feed rate (f) and depth of cut (doc) increase the cutting power (Ne). This occurred in both situations since the cutting force (Fc) increases due to the larger shear plane area (Fuh and Chang, 1997; Manna and Bhattacharyya, 2003; Ng *et al*., 2006). Fig. 5b shows that increasing the depth of cut (doc) and feed rate (f) considerably increase the cutting power (Ne). In Fig. 5a it is observed that cutting with higher levels of the cutting speed (Vc) and depth of cut (doc) considerably increases the cutting power (Ne). That occurred due to simultaneous increase of the main shaft rotation and of the cutting force because of the depth of cut (doc) increment (Machado *et al*., 2009).

Figure 5c show that application of a cutting fluid (Lub: +1) reduced the cutting power (Ne) under all cutting conditions but when cutting the 7075-T6 alloy with the lower level of the cutting speed (Vc). In this case the cooling action of the cutting fluid may have played important hole.

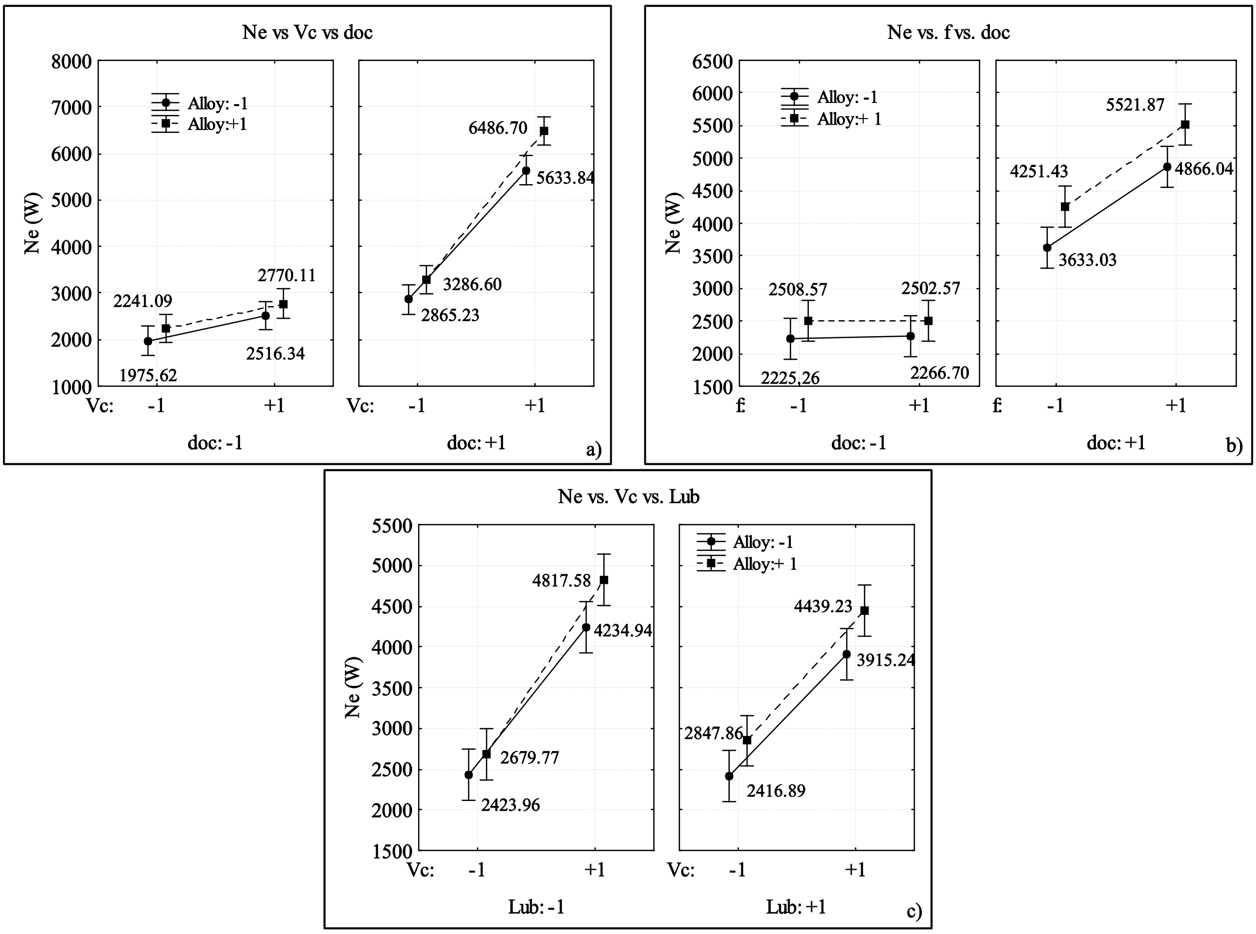

Figure 5. a) Influence of Vc and doc on the Ne; b) Influence of f and doc on the Ne; c) Influence of Vc and Lub on the Ne

4. CONCLUSIONS

The results of this investigation allow the following conclusions to be drawn.

Increasing the cutting speed reduced the cutting force (Fc) and increasing the feed rate (f) and depth of cut increased it. High cutting speeds generate high temperatures and consequently soften the work material at the shear planes facilitating the cut.

The cutting power is one of the main characteristic of machinability which depends upon the cutting force (Fc) and cutting speed behavior during the aluminum alloy machining. It has been seen that increasing the cutting speed and changing any parameter that increase cutting force will increase the cutting power. Under high productivity, that is, a combination of high cutting speed and high feed rate and depth of cut strongly increase the cutting power. The free-cutting elements present in the 6262-T6 alloy have shown positive effect in the cutting force and in the power consumption. The harder 7075-T6 alloy presented higher forces and power consumption than the softer 6262-T6 alloy when turning them. Application of cutting fluid tends to reduce the cutting power due to the lubrication action but this was not statistically significant.

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