Design of Experiment Machinability Evaluation of Dry Drilling Machinability of Recycled 3003 and 5052 Aluminum Alloys

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Abstract - *Currently, the machining of recycled aluminum alloys is developing. It is therefore time to have the necessary resources to master the machinability of these alloys. When machining any alloy, knowledge of certain characteristics to guarantee the quality of mechanical parts is very important. To continue the research on the machining of these alloys, we focused this study on the dry drilling machinability of recycled aluminum alloys. The focus is on two types of aluminum alloys from beverage cans. For the machinability of these alloys, three characteristics are taken into account, namely, the cutting force, the morphology of the chips and the concentration of metal particles that can be influenced by the feed and cutting speed. In this study, the results that show the link between machinability characteristics and cutting parameters are presented. Models have also been established for the evaluation of machinability.*

Key Words **:** machinability, dry drilling, cutting force, chip morphology, metal particles

1.INTRODUCTION

The recycling of aluminum alloys has seen a growth in interest and applications over the past forty years and has become another effective way to produce aluminum parts. Among many recycled aluminum products, there are beverage cans. These beverage cans are usually recycled to produce other cans or other objects. Everything that is produced on the basis of recycled cans remains until now on the margins of the production of mechanical parts that can be obtained by machining. Some industrial sectors already use recycled aluminum parts (shaped by deformation), not from beverage cans. While there are other parts that need to be shaped by material removal, such as drilling. To use recycled aluminum, it is necessary that a study be carried out. This study must globalize recycling methods and treatment. With the aim of improving aluminum recycling techniques, A.R Khoeia and al [1] developed a robust design method, which consisted of experimentally analyzing the effects of process parameters. They suggested that to have a good recovery of the material, it is necessary that the high level of the temperature of the furnace is controlled. They also observed that furnace temperature and loaded quantity have a major influence on the total variation in recovery. M. Samuel [2], presented a new direct technique for recycling aluminum waste with low energy consumption and costs without involving metallurgical processes. The experimental results obtained show that the direct technique for recycled aluminum allows high productivity and about 80% green density before sintering. From existing processes, Eulogio Velasc and Jose Nino [3] in their work, showed the need, during the transformation of the alloy, to control, remove impurities and inclusions hydrogen and excess magnesium.

All machining always generates cutting forces, which are the result of the shear and friction forces exerted by the tool on the part. Knowledge of cutting forces is necessary for the control of the power required for cutting, the mechanical efficiency of the machine tool, the dimensioning of machine components, the prediction of the deformation of parts. Cutting forces are involved in machining precision, in the formation of the surface finish, in the process of chip formation. Finally, the cutting forces being related to the mechanical properties of the material, are likely to provide information on the machinability of the machined material. Several parameters influence the cutting forces during machining, including: feed per revolution, cutting speed, cutting depth, geometry and coating of the tool.

Many experimental techniques have been exploited to examine the cutting force. Thus, we note the implementation of certain analytical models, such as that of Merchant [4] and [5]. It is a model in which three physical phenomena are considered. The first concerns the law of conduct. It uses a Bridgman [6] model from 1952, which does not take into account temperature and strain speed. The second, considers a constant friction at the interface between the tool and the chip. The third concerns the formation of the chip along the shear plane. Taking into account the importance of parameters and cutting conditions, in the phenomenon of cutting forces, M. C. Shaw [7] showed that the very low cutting speed, of the order of a few hundred m/min or less, has no influence on the cutting forces. This is confirmed by E. Morin and al [8], specifying that the nodal force (Fn) and the moment (M) are a function of the advance per turn. During drilling of aluminum alloy, E. J. A Armarego [9] had proposed a method for the study of the nodal force with the consideration of the geometry of the drill. According to J. Masounave and al [10] dry machining causes an increase in temperature in the cutting area, and can influence the nodal force. Similarly, Moufki and al [11] hypothesized that constant friction increases the temperature and proposed taking into account the temperature at the interface to vary the coefficient of friction. Zemzemi and al [12] showed that the coefficient of friction decreases strongly with the speed of sliding of the chip on the cutting face.

The formation of the chip is also a characteristic for the evaluation of machinability, because the phenomenon of chip formation involves a large number of parameters, such as the different machining parameters, the nature of the tool-material contact and the rheology of the machined material. According to G. Carro Cao and al [13] the understanding of the various phenomena during machining needs to be observed, for example, by microcinematography, as was done by G. Warnecke and al [14]. The formation of the chip depends on its morphology, and it is also very important for the evaluation of machinability, the mastery of which remains a challenge during machining for economic reasons related to chip management. These chips are classified into three categories by G. List [15], continuous chips, chips with edges and discontinuous, segmented or scalloped chips. The generation of surfaces by machining systematically leads to the production of chips that have shapes according to the cutting parameters. From a macrographic point of view, according to ISO DIS 3685, the shape of chips varies and depends on machining conditions and tool/material pair. Krishnam and Irusa [16] studied 6063-T6 aluminum chips obtained under dry cutting conditions, with abundant lubrication and MQL. Depending on the cutting speed J. Kouam and al [17] studied aluminum chips A319 T0 and T6, A356-T0.

In general, machining generates very high temperatures, sometimes forcing the use of R. Khettabi lubricants [18]. Except that the use of lubricants increases machining costs and presents difficulties for chip recycling. To avoid these difficulties, dry machining is therefore used. But dry machining produces metal particles of micron and nanometric sizes that oxidize in air and remain suspended for a long time depending on the concentrations. The presence of these metal particles in the air endangers the health of machinists. B. Levresque and al [19] specified that the machinist spends on average 90% of his time in his workplace, which contains many substances likely to harm his health confirmed by W. G. Kreyling and al [20], and their concentration is variable in space according to X. Yang and al [21], C. Ostiguy and al [22]. B. Balout and al [23] have shown that the amount of fine particles produced is influenced by the material and the heat treatment it has undergone, the temperature and the formation of the chip. V. Songmene and al [24] showed that the depth of cut has an influence on the particulate emissions in drilling of alloy 6061 – T6 and A356. The production of these particles is very important at the beginning of machining and decreases when the depths are a little greater. They also showed that particulate emissions during the cutting process are a function of the material. Ductile materials generate more fine and ultrafine particles than brittle materials, as there is a correlation between chip formation and particulate emissions.

This study was therefore carried out, with the aim of providing a partial solution, related to the problem on the machinability of the various recycled aluminum alloys. Two recycled aluminum alloys named 3003-R and 5052-R, respectively from the bodies and lids of beverage cans, were used to define their machinability in dry drilling. This study gave a certain amount of information on the dry drilling machinability of these two recycled aluminum alloys. This information will allow a safe realization of parts made of these recycled alloys in the same way as other materials. The study therefore consisted in studying the influence of cutting parameters (feed and cutting speed) on cutting forces, chip morphology and mass concentration of metal particles. For this, relationships were established between cutting force and cutting parameters as a function of feed and cutting speed, cutting force and chip morphology as a function of feed per revolution, metal particles, chip morphology and feed.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the process of obtaining the recycled aluminum bars that were used to perform the tests. The process consists of two phases. The first phase is that of preparation (recovery of cans, sorting and separation, washing and cleaning). The second phase is production (grinding, heating and melting, and spinning). The point on separation consisted in separating the body of the can (aluminum + Manganese) from its lid (aluminum + Magnesium). Each was fed into the mill to obtain crushed material (Figure 1). The crushed metal is poured into a device to perform spinning. On the device are mounted four heating rings (200 ° C, 450 ° C, 550 ° C and 650 ° C). The ground metal, heated successively until melting, is pushed automatically and slowly by a piston at a constant speed. The bar obtained from the body is called "alloy 3003-R", and the lid "alloy 5052-R".

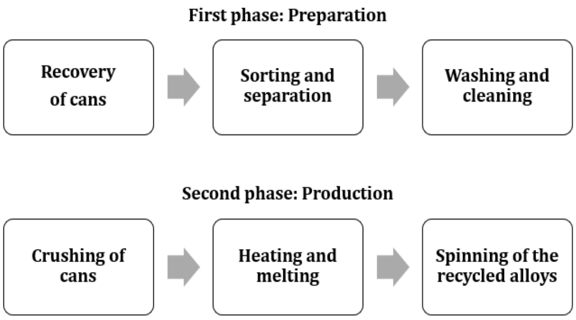

Fig-1: Process for obtaining recycled aluminum bars

Figure 2 shows the microstructure of each alloy, observed with the Scanning Electron Microscope (SEM) in figure 3. The non-homogeneous distribution of precipitates in the two alloys is observed. Similarly, the observation of the presence of pores of different dimensions and shapes and, of non-homogeneous localization is made. This porosity remains permissible because it is specific to N. Roy foundry alloys [25].

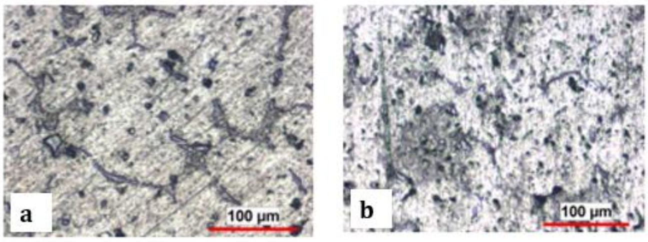

Fig-2: Microstructure of recycled alloys: a) Alloy 3003-R, b) Alloy 5052-R

The same microscope was used for observation, analysis and segmentation of chips, and also to define the chemical composition of each alloy (Table 1).

Table-1 : Chemical composition of each alloy (%)

alloys	Al	Cr	Si	Fe	Cu	Mn	Mg	Zn
3003-R	97	-	0.3	0.2	0.25	1.5	0.5	0.25
5052-R	94.85	0.1	0.3	0.4	0.1	0.3	3.8	0.15

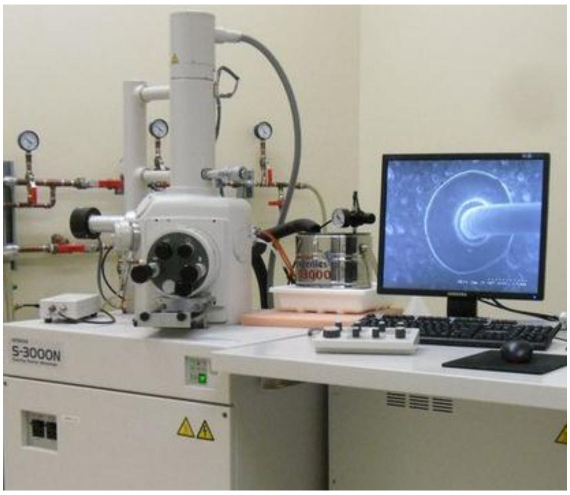

Fig-3: Scanning electron microscope (SEM)

The round bars obtained from the production process set up, were premachined to obtain prisms that served as samples for machinability tests.

The drilling operations were performed on a Huron K2x10 Graffenstaden 3-axis CNC milling machine (Figure 4), having a rotation frequency of 28000 rpm and a cutting feed of 30 m/min, a power of 40 kw, a torque of 50 Nm, an axis acceleration of 6m/s^2 and a resolution of 1µm. The operation carried out was a drilling of diameter 8 mm and depth 12 mm, with a HSS BLACK OXIDE fort with conventional gouges, tip angle of 118°, propeller angle of 35° and core diameter of 2 mm.

Fig-4 : CNC milling machine Huron K2x10

Several input parameters are used to study the cutting force, the mass concentration of metal particles and the morphology of chips as a machinability criterion. In this study, two parameters were considered advance and cutting speed to study cutting force. The advance is considered for the morphology of chips and the mass concentration of metal particles.

The response surface type experimental design was used to investigate the influence of these parameters on cutting force. Table II shows the experiment matrix.

Table-2 : Experience matrix

	f (mm/rev)	Vc (m/min)
Haut	0.03	100
Centre	0.115	155
Bas	0.2	210

Initially, the multifactorial method made it possible to organize and execute the experiments in an optimal way in order to obtain the input parameters most influencing the cutting force. These experimental designs provided graphs of direct actions and ANOVA for determining the influence of each parameter.

In a second step, and in view of the results of the analysis from direct action graphs and ANOVA, the unifactorial method was used. This method consisted in defining the effects of the parameter most influencing on, the cutting force, the morphology of the chips and the mass concentration of the metal particles.

3. RESULTATS ET DISCUSION

3.1 Cutting forces

The cutting forces were measured, the data obtained was converted to be read by the Matlab software. This acquisition was made for both recycled alloys, and for each machinability test, according to the experimental design from the analysis of all the images obtained, only the cutting force Fz was retained. The other cutting forces Fx and Fy being very weak, were not taken into account.

With regard to the direct effects, for alloy 3003-R, of chart 1, one observes the difference between the effects of the advance with respect to the cutting forces, and the cutting speed with respect to the cutting force. The effect of advance on cutting force for both alloys is remarkable. Indeed, the cutting force is high when the advance per turn increases. This is not the case for the cutting speed, whose effect is almost ineffective.

What is observed for alloy 3003-R is the same for alloy 5052-R.

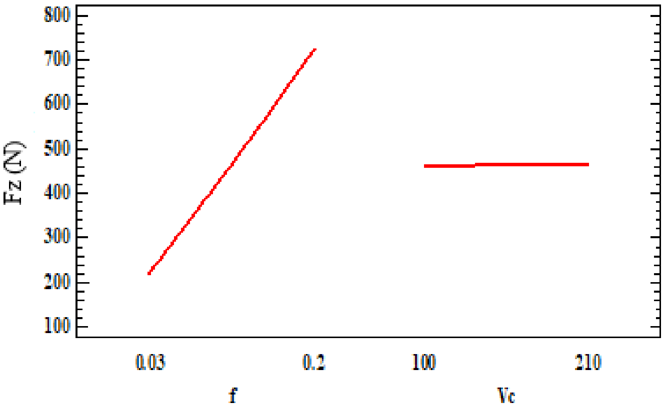

Chart-1: Graph of direct effects of alloy 3003-R

The analysis of the results, made it possible to observe for the two recycled alloys, that the cutting force Fz increases when the feed changes from 0.03 to 0.2 mm/rev. The cutting speed of 100 to 210 m/min shows almost no change. The ANOVA analysis in Table 3 showed that the cutting force Fz can be evaluated as a function of advance for recycled alloys 3003-R and 5052-R, and as a function of advance. Statistics R ^{2} explain 99.99 % variability in the cutting force Fz of the two recycled alloys 3003-R and 5052-R. There is therefore a very strong relationship between the advance and the cutting force of recycled alloys.

Table-3 : ANOVA of the cutting force Fz

Source	DDL	Sum of squares	Average quadratic	Rapport F	Proba
		ANOVA Fz 3003-R R^2= 99.99%			
f	1	366449	366449	445681.59	0.0000
Vc	1	3.84	3.84	4.67	0.074
f-f	1	8482.56	8482.56	10316.63	0.0000
		ANOVA Fz 5052-R R^2= 99.99%			
f	1	473923	473923	566733.92	0.0000
Vc	1	3.87207	3.87207	4.63	0.0749
f-f	1	21769.5	21769.5	26032.76	0.0000

The machinability tests made it possible to understand, for the cutting force Fz of recycled alloys 3003-R and 5052-R, that the advance has a significant, positive and higher effect. The effect of advance is followed by that of the interaction advance - advance. Cutting speed and other interactions on cutting force Fz have no significant effects. The results of this analysis led to the conclusion that the cutting force is influenced by the advance. By keeping the cutting speed fixed at 100 m/min, the results showed that the cutting force also depends on the nature of the alloy. To express the cutting force, Armarego and al [9] used the parameters of the relation (1), and J. Masounave et al [10] those of the relation (2).

$$F_n = A \,.\, f^{\alpha} \,.\, D^{\beta} \,.\left(\frac{2\,.\,w}{D}\right)^{\gamma} .\, 2 \,.\, P^{k} \,.\, \delta_o{}^{l} \,.\, \psi^{m} \tag{1}$$

$$F_n = A \,.\, f^{0,8} \,.\, (T - T_{su})^{n} \tag{2}$$

With: Fn (nodal force), A (constant), f (feed), α, β, γ, n, m, k, l (influence coefficients), D (drill diameter), 2w (Drill core length), 2P (drill tip angle), (δo Propeller angle), ψ (Central edge angle), T (Macroscopic part temperature), Tsu (Solidus temperature in material machining).

In this study, some parameters considered by Armarego and al [9] and J. Masounave and al [10] (β, γ, n, m, k, l, D, 2w, 2P, δo, ψ, T, Tsu), were not considered. Only the coefficient α, which is a coefficient of influence relative to the nature of the material. Like Mandatsy Moungomo and al [27, 28], the cutting force Fz was expressed as:

$$Fz = A.f^{\alpha} \tag{3}$$

Keeping the cutting speed constant at 100 m/min, further tests were performed on the same samples. The values of the cutting force measured (Table 4), made it possible to observe the evolution of the cutting forces Fz as a function of the advance. The results obtained are in line with those of Mr. C Shaw [7], by the fact that the cutting speeds used are low. A comparison between the cutting forces of the two alloys was made. At one advance per turn of f = 0.03 mm/rev, there is a slight difference in cutting force. The data obtained are shown in Table 4.

Table 4 : The cutting force data obtained at Vc = 100 m/min

	Force de coupe Fz (N)	
f	**3003-R**	**5052-R**
0.03	**218.2**	**154.8**
0.05	**262.6**	**245**
0.07	**331.9**	**348**
0.11	**436.6**	**456**
0.15	**575.9**	**568.5**
0.2	**714**	**718**

Chart 2 shows the evolution of the cutting forces Fz for the machining of the two recycled alloys.

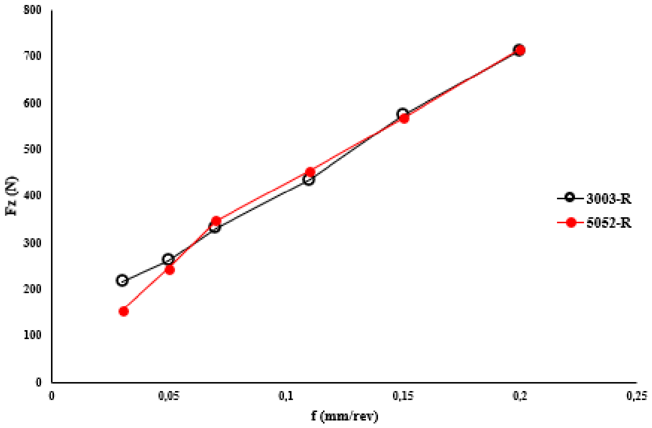

Chart-2: Evolution of the cutting force of alloy 3003-R and 5052-R as a function of the advance at Vc = 100 m / min.

The results of the analysis of this evolution have shown the existence of strong and significant relationships between cutting force and advance. Models 4 and 5 for the evaluation of the cutting force Fz have been deducted. By the value of the coefficient α, and the constant A, it is clearly observed that the nature of the alloy also has an influence on the cutting force.

$$Fz_{(3003-R)} = 1893.3 * f^{0.639} \tag{4}$$

$$Fz_{(5052-R)} = 2626.5 * f^{0.79} \tag{5}$$

3.2 Morphology of chips and emission of metal particles

This analysis consisted in observing the morphology of the chips, produced during the dry drilling of recycled alloys 3003-R, 5052-R. The input parameter taken into account is the feed (ranging from 0.03 to 0.2 mm/rev) and the constant cutting speed at 100 m/min. The output data are the chips taken and observed. Figure 5 shows an extract of the chips obtained during the drilling of these recycled alloys. The results show that the morphology of the chips is almost identical for both recycled alloys (Figure 5a for alloy 3003-R and 5b for alloy 5052-R). From 0.03 to 0.07 mm/rev, the chips are short and comparable to a stack of cylinders of different diameters. Beyond 0.07 mm/rev, up to 0.2 mm/rev, the chips are fragmented (Figure 5c for alloy 3003-R and 5d for alloy 5052-R). The results show a difference in the evolution of chip morphology as a function of advance. Overall, the chips of alloys 3003-R and 5052-R are long and helical when the feeds are very low. As the advances increase, all the chips become fragile.

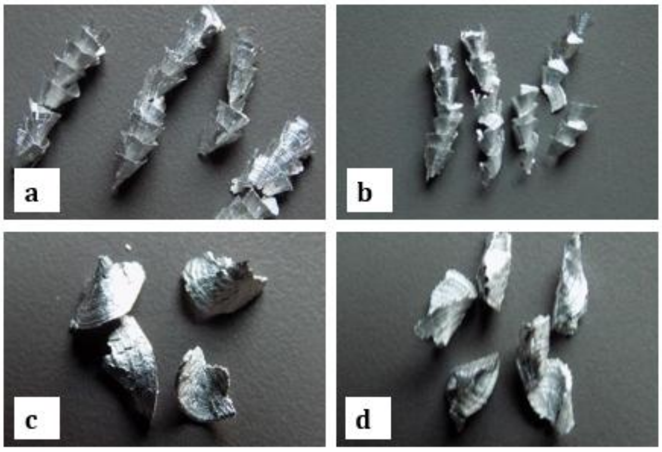

Fig-5: Morphology of alloy chips: a, b) Chips of alloys 3003-R and 5052-R, f = 0.03 to 0.2 mm/rev; c, d) Chips of alloys 3003-R and 5052-R, f = 0. 7 to 0.2 mm/rev

When comparing these chips with those of alloy A356-T0, which was machined under the same conditions and with the same parameters, no difference in morphology was found (Figure 6). These results confirm once again that foundry alloys are generally brittle, and this brittleness promotes chip fragmentation.

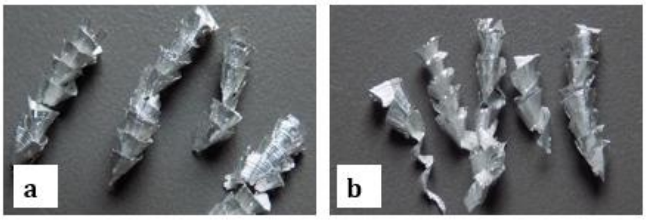

Fig-6: Alloy chip morphology, f=0.03 mm/rev (a) Alloy 3003-R chips; (b) Chips of alloy A356-T0

At a constant cutting rate of 100 m/min, chip segmentation was made and observed under a scanning electron microscope. Figure 8 shows an extract of the segmentation of the alloy chips, for the advance 0.03 mm/rev (Figure 7a), for the advance 0.2 (Figure 7b). The morphology of chips and its segmentation depends on the properties of the alloys, but also on the parameters and cutting conditions. Therefore, for a given alloy, a change in these data can modify the morphology and segmentation of the chips, Xie and al [26]. In this figure, the image on the left shows the chip sampled and magnified 15 times. The image on the right, a selected part of the chip, shows the segmentation of the chip, magnified to 500 times.

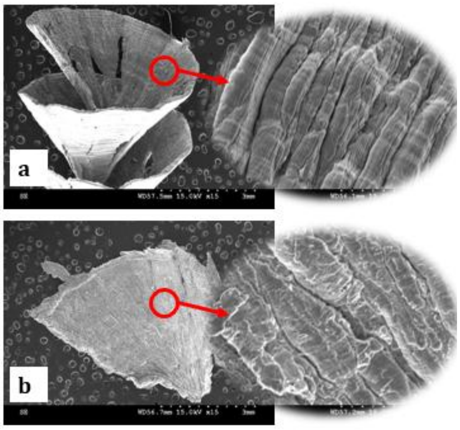

Fig-7: Segmentation of alloy chips: a) at f=0.03 mm/rev; b) A f=0.2 mm/rev

The analysis shows that when the feeds are low, f = 0.03 mm/rev for example, the segmentation of chips is almost the same for recycled alloys 300 3-R and 5052-R. Although the morphology of the chips is almost identical, a difference was observed between the segmentation of recycled alloys 3003-R, 5052-R.

Machining by varying the feed (0.03 to 0.2 mm/rev) was done, at a constant cutting speed (100 m/min), to measure the mass concentration of metal particles (Table 5).

Table 5 Mass concentration data of metal particles obtained at Vc = 100 m/min

	Mass concentration of metal particles (mg/m^3)	
f	**3000 R**	**5000 R**
0,03	57900	59500
0,05	51240	52916
0,07	45111	43111
0,11	24800	22400
0,15	20750	21250
0,2	19000	18000

The study of metal particles has shown that for any alloy machined, the concentration of particles is higher at the beginning of machining, and low at the end of machining, as indicated by V. Songmene and al [24]. The analysis of the data made it possible to establish, for each alloy, correlations between:

- The emission of metal particles and the morphology of chips.
- The emission of metal particles and the advance.
- The emission of metal particles and the cutting force.

The analysis shows that when the chips are long and helical, the mass concentration of metal particles is high. When chips are short and fragmented, the mass concentration of metal particles is low. The change in segmentation between recycled alloys shows its relationship with the mass concentration of metal particles. An analysis was made to show the existence of a relationship between the mass concentration of the metal particles and the morphology of the chips. Because of the friction of the chips on the cutting tool, which causes wear, their morphology can be influenced. No wear of the cutting tool was found

Chart 3 shows the evolution of the mass concentration of metal particles. Metal particles are higher when advances are smaller. These results also show the existence of a relationship between the mass concentration of metal particles and the advance.

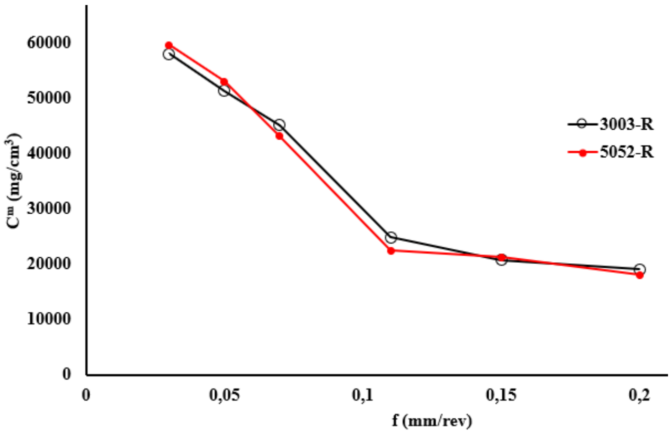

Chart-3: Evolution of s metal particles of alloy 3003-R and 5052-R as a function of the advance at Vc = 100 m / min

Formulas 6 and 7 represent experimental models that follow a logarithmic form with an R2 statistic of 0.94. These formulae could be used to evaluate the mass concentration of metal particles, depending on the advance in machining recycled alloys 3003-R and 5052-R.

$$C^{m}_{(3003-R)} = -23265\ln(f) - 21213 \qquad (6)$$

$$C^{m}_{(5052-R)} = -24605\ln(f) - 24804 \qquad (7)$$

The analysis of the curves of figures 7, 8 and 9, showed the existence of a link between the morphology of the chips and the concentration of metal particles. During the analysis of chips, it was found that short chips were obtained at feeds per turn ranging from 0.03 mm/rpm to 0.07 mm/rpm, and fragmented chips from 0.11 mm/rpm to 0.2 mm/rpm. This led to the conclusion that the concentration of metal particles is higher when the advances per turn are small. Therefore, to reduce the emission of metal particles, during dry drilling of these two alloys, there is a need to increase the feeds per revolution.

The correlation between the cutting force and the metal particles is given by relations 8 and 9. From these relationships, it is understood that the mass concentration of metal particles is higher when the cutting force is low and smaller when the cutting force is high.

$$C^{m}_{(3003-R)} = -35898\ln(Fz) + 250458 \qquad (8)$$

$$C^{m}_{(5052-R)} = -30611\ln(Fz) + 21699 \qquad (9)$$

4. CONCLUSIONS

This study provided some information on the influence of cutting parameters on the drilling machinability of recycled aluminum alloys. The results obtained showed the influence of the feed, the cutting speed on the machinability of each recycled alloy.

The cutting speed has no influence on the cutting force for all recycled alloys. The advance has an influence on the cutting force. At a constant cutting speed of 100 m/min, the cutting force increases with the increase in the feed.

The chips of recycled alloys, obtained according to the advance, at a cutting speed of 100 m/min, have similarities. They are long and helical with low feeds (less than 0.1 mm/rpm), short and fragmented with strong feeds (greater than 0.1 mm/rpm). Like virgin aluminum alloys, recycled alloys 300 3-R and 5052-R exhibit good machinability performance in dry drilling.

This study also made it possible to understand that machinability in dry drilling is also a function of the nature of the material.

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