CIRP Journal of Manufacturing Science and Technology 7 (2014) 210–221

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Review

Performance of the jatropha vegetable-base soluble cutting oil as a renewable source in the aluminum alloy 7050-T7451 milling

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ARTICLE INFO

Article history:
Available online

Keywords:
Cutting fluids
Jatropha
Aluminum alloy
Milling
Machining
Aeronautical industry

ABSTRACT

This article aimed at collecting data on the performance of a new product – the jatropha vegetable-base soluble cutting oil – in relation to other canola oils (vegetable), synthetic (jatropha ester), and the semisynthetic (mineral) traditionally used in the industry in high feed milling of the aluminum alloy 7050-T7451 for the production of aeronautical structures. Thus, information on requisites, restrictions, and machinability criteria for the cutting oils were analyzed. It was observed that the jatropha cutting oil presented the best results in relation to requirements for lubrication, superficial mean roughness index Ra, and shape errors, which were measured in the milling part. It also offered an increase in the life-span of the cutting tool that exceeded in approximately 30% the other cutting oils analyzed here. The jatropha (vegetable) oil, in relation to its physicochemical properties, appeared to be the best one fit for being used in the machining of aluminum alloys 7050-T7451 because it did not interfere with any of the elements involved in the formation of intergranular corrosion and/or pitting, which are not allowed in the aeronautical production of parts. Jatropha (vegetable) cutting oil, besides being produced from a clean and renewable source, has the inherent characteristics that can help attain a sustainable manufacturing.

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1. Introduction

In 2009, it was estimated that approximately 39 million tons of lubricants had been used in machine tools around the planet and, furthermore, an increase of 1.2% is previewed for this decade. Out of this amount, about 85% is of petroleum-based oils [1] that derive from a non-renewable source. As machining is one of the preferred processes in manufacturing, in general, the utilization of lubricants and coolants might represent a value ranging from 7% to 17% in the manufacturing cost, which has a direct influence upon competitiveness [2–4].

The basic functions of a cutting fluid are the cooling of the part tools, as well as the lubrication of the interface of tool and cutting chips, and the flow of materials from the cutting area. Especially in the production of structural aeronautical parts in aluminum alloys that present a high thermal coefficient of expansion ΔL (from

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http://dx.doi.org/10.1016/j.cirpj.2014.04.004
1755-5817/

$23 \times 10^{-6.1}$/K against $11 \times 10^{-6.1}$/K of steel) and a low elasticity module (approximately 1/3 of the elasticity module (E) of carbon steel), which always implies re-working the part, the cooling property of the cutting fluids prevents bending situations [5–13].

However, the application of a cutting fluid in the machining of structured aeronautical parts of aluminum alloy must consider the need of control and prevention against all sorts of aluminum corrosion, such as the uniform corrosion by pitting, exfoliation or intergranular corrosion. This occurs because cutting fluids of chloride-base are catalyst agents of corrosion in the seeds outline, and they can generate internal cracks that will interfere with their endurance and might lead to the materials fatigue. Besides chloride, other groups of substances, such as nitrosamines, formaldehyde condensate, phosphorus, and polycyclic aromatic hydrocarbons can cause problems to part quality (e.g. paint stains) and to occupational health (e.g. a case of dermatitis in the machine operator). Silicon, as well, cannot be used as an anti-foaming additive because it interferes with the paint quality of parts [8,14–22].

This article, besides focusing on the approach to the ongoing milling process, is centered on aspects of the rational use of cutting fluids according to environmental parameters, which means reducing consumption of potable water and the use of materials to improve manufacturing requirements while controlling and monitoring cutting fluid maintenance with less environmental damage. Thus, the choice of the cutting fluid emulsifier becomes crucial in this study. About 70% of the lubricants used in the industry are of mineral-base (petroleum), mostly because of their infrastructure for extraction, production, and the logistic required for these products. Nevertheless, their inherent toxicity and non-biostability nature make mineral-base oils a constant environmental threat to the soil and water reserves and sources. Synthetic-base oils have, at the same time, a lower lubricant capability and a higher cooling capacity than the other bases. As, in general, industries do not have efficient management systems that offer alternatives of correct disposability of these products, the use of these non-degradable components is regarded as high-risk environmental threats [23–26].

Another option to examine is the use of vegetable-base cutting oils, which apart from being considered as resources derived from renewable sources, they can guarantee better lubricant power due to the polarity of their molecules. However, they require quite a complex management because of the proliferation of microorganisms that modify their mechanical and physicochemical properties [13,27–29].

Among vegetable-base oils, the jatropha vegetal (*Jatropha curcas* L.) is an oleaginous plant with a high level of oil in its natural composition (from 52.54 to 61.72% of seed oil). This plant is a species that demands much insolation and it has a high level of resistance to drought so that it can be viewed as a good agricultural option for semi-arid areas, with a yielding capacity of two tons of oil per hectare. Jatropha is a native Brazilian vegetable that does not integrate the food chain so that this product has a high

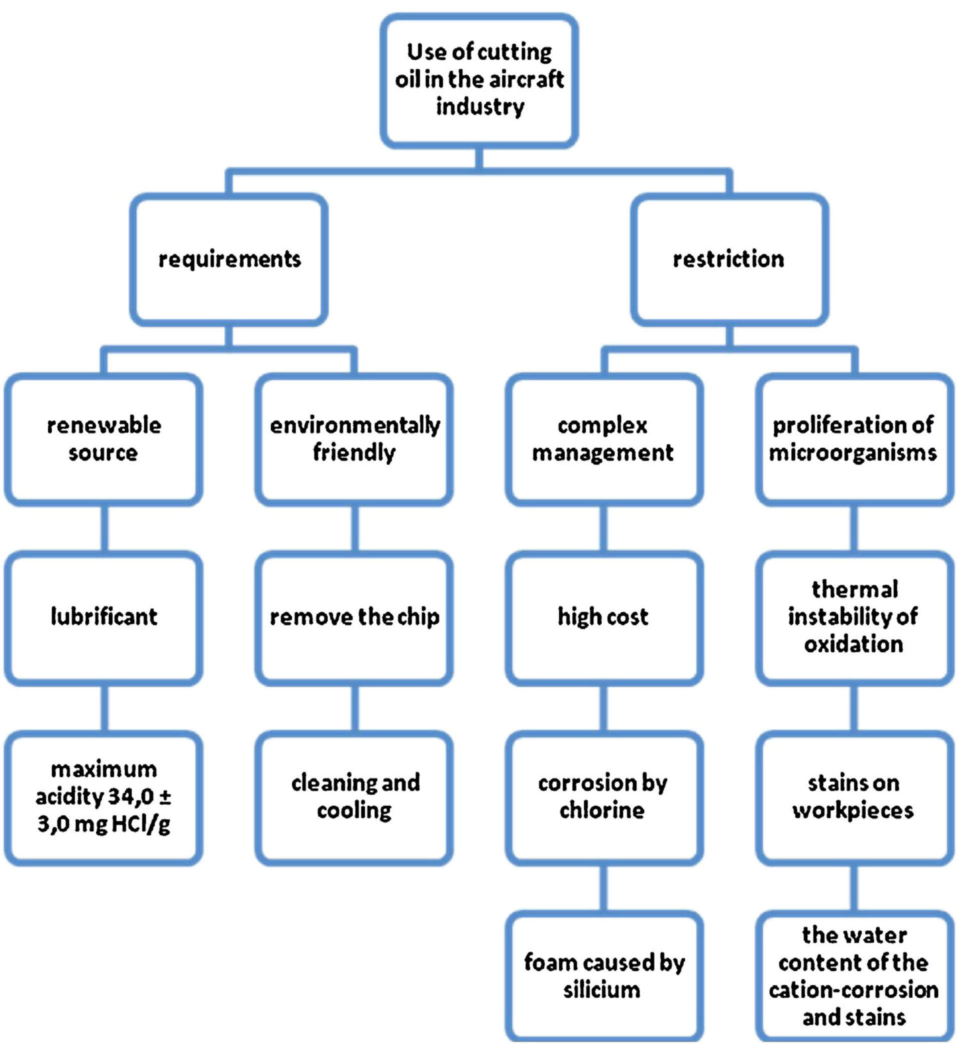


Fig. 1. Requirements and restrictions for the use of cutting fluid in the aeronautical industry.

potential for research aiming at developing a soluble cutting oil [13].

Fig. 1, in a general way, shows the main requirements and restrictions to be used as parameters for evaluating the efficiency of these cutting fluids in the milling process of aeronautical structured parts of aluminum alloy.

The present article offers a comparative performance evaluation of the jatropha oil, which is a new product, that stemmed from a renewable source, both in natura as in its synthetic-base (jatropha ester), in relation to the oils of canola (vegetable) and semisynthetic (mineral) that are typically used in milling, considering the requisites and restrictions for the production of aeronautical aluminum alloy components.

The following criteria were used in this analysis:

- Milling analysis for the use of different cutting fluids.
- Dimensional analysis of the aeronautical part with the use of distinct emulsions of cutting fluids.
- Analysis of physicochemical elements of cutting fluids and their influence upon the properties of these parts.

2. Materials and methods

2.1. Materials and methods for machining experiments

The milling experiments were carried out at the machining center HERMLE C600U, which has the maximum rotation of rpm, maximum speed [v_c] of 35 m/min and 15 kW power/output [P]. Raw material used in the machining process were blocks of aluminum alloy (7050-T7451 (6.2% Zn–2.3% Cu–2.2% Mg–0.2% Zr), usually applied in the project for machining components of aeronautical structures.

Initial experiments on the life span of the tool, machined surface analysis, the tool wear and tear mechanism, chip shape and cutting power were carried out in test specimens that presented flat surfaces measuring 355 mm × 320 mm × 100 mm. In these experiments, square end mills, 50 mm of diameter [Ø], four teeth with interchangeable inserts of hard metal LNAR 1106 PN-N-P-Iscar was utilized. Five cutting tools were used in each combination of cutting parameters to test the tool working life and, as a result, the mean flank [V_B] (mm) wear was calculated as well as the standard deviation [σ] (mm) for these values in each performed measuring.

Machining process was evaluated according the following machining criteria:

- The wear flank [V_B] (mm) of the cutting tool.
- The wear mechanism of the cutting tool.
- The chip shape produced.
- The cutting speed [v_c] (mm/min).

In the test for the life span of the cutting tool, measurements were made of machinability criteria at each 14 complete facings of the surface, totaling the average machining length of 42 m. Cutting movement was in a concordant direction. The cutting speed [v_c] was used with a constant of 1884 m/min, which corresponded to the maximum rotation [n] attained in the machine tool test. The axial cutting depth [a_p] was established at 2.88 mm and tool penetration [a_e] at 75%.

Table 1 shows the tooth used in the milling tests on flat surfaces. The values were determined for the increase and decrease cutting temperature and to analyze the effects of lubrication and/or cooling in the test with cutting fluids. The short tooth aimed at increasing the interface tool and chip temperature and, consequently, at evaluating the cooling power and, as the cutting tooth was increased, the goal was to heed to the increase of the lubricant effect and, hence, to temperature decrease. This evaluation proceeded indirectly since it was not possible to measure either the temperature or the tribological characteristics of these testing procedures.

Table 1
Cutting parameters for tests of life on a flat surface.

Combination	Cutting speed, v_c (m/min)	Feed, f_z (mm/tooth)
1	1884	0.05
2	1884	0.15
3	1884	0.3

In the evaluation of the cutting tool flank wear [V_B], tool mill inserts were measured with a microscope Wild M3C of Herrbrugg Switzerland type S, with a power increase of 6.4×, 16×, 25× and 40×, software Leica Qwin Pro. For checking of the type of wear and the formation of wear mechanism in the cutting, an electronic scan microscope [MEV], Phillips, model XL30 was used. 49 cutting conditions were combined based on 7 feed rate conditions [f_z] and 7 cutting speeds [v_c], according to the evaluation tests for the quality of the machined surface (roughness index Ra) and chip quality, as shown in Table 2. The same values for axial cutting depth [a_p] of 2.88 mm and for tool penetration [a_e] at 75% for checking roughness index Ra, which were the same values used in the test for the cutting tool life.

The aim of analyzing the variation of cutting speed and tooth values combined was to offer a gradient for increasing and decreasing temperatures in the cutting process. It was verified what the lubrication and cooling effects of the cutting fluids in the milling process under analysis had been, and also whether significant variations had occurred in the surface roughness [Ra], that is, in the surface quality of the produced. The influence of physicochemical properties of the cutting fluids with the increase of feed rate [f_z] was also analyzed.

For each machined face, three values of Ra (start, middle, and end of the part) were measured, and the end value was the mean value among the three of them. Measuring was made with a portable rugosimeter MITUTOYO, model SJ-201P, in the direction of the feed rate, with a cut-off of 0.8 mm for $0.1 < Ra \leq 2$ and a cut-off of 2.5 mm for $2 < Ra \leq 10$, according to the ISO 4287/2002 norm. According to the norm of the aeronautical industry (MEP 08-020 ENG_REVB [30]), the maximum roughness index Ra limit permitted for machined surfaces of aeronautical parts is [Ra] of 3.2 μm. Cutting forces were measured by a piezoelectric platform consisting of a dynamometer Kistler (model 9265B), an amplifier Kistler (model 5070, 8 channels with a sampling degree of 1000 HZ/channel), a capture board PCIM-DAS 1602/16 and software DynoWare 2825A.

According to measurement methodology used here, cutting forces were measured in each cutting tool in the machined length of 84 and 168 m, totaling 10 values of measured cutting force with the 5 cutting tools in the test for tool life. The end of cutting force [F_c] in each combination of cutting fluid and feed rate [f_z] was the

Table 2
49 combinations of cutting parameters.

		Feed, f_z (mm/tooth)						
		0.05	0.08	0.12	0.20	0.25	0.30	0.35
Cutting speed, v_c (m/min)	219	1	2	3	4	5	6	7
	314	8	9	10	11	12	13	14
	628	15	16	17	18	19	20	21
	942	22	23	24	25	26	27	28
	1257	29	30	31	32	33	34	35
	1571	36	37	38	39	40	41	42
	1884	43	44	45	46	47	48	49

mean of the 10 measures and, therefore, the standard deviation σ of these values was calculated.

The milling of a part, in compliance to the required characteristics for the complex surface of aeronautical parts, was made so that a model part (Fig. 2B) was produced in order to simulate a real manufacturing situation, including all the possible effects of the various distinct cutting fluids upon the quality of the part. An uncoated solid hard metal mill was used for chipping, with a chip breaker and three teeth, 16 mm of diameter, edge radius of 1 mm, axial cutting depth [a_p] of 4 mm, and tool penetration [a_e] at 70%. For the finishing, an uncoated, straight top solid hard metal mill, 2 teeth, 16 mm of diameter, axial cutting depth [a_p] of 5 mm with tool/work penetration [a_e] at 20% was used. Sample-specimens for the milling of complex surfaces had 100 mm × 200 mm × 400 mm. Table 3 presents the cutting parameter values for complex surface machining.

Dimensional allowances were established in agreement with the aeronautical plant floor limits for the manufacturing of its

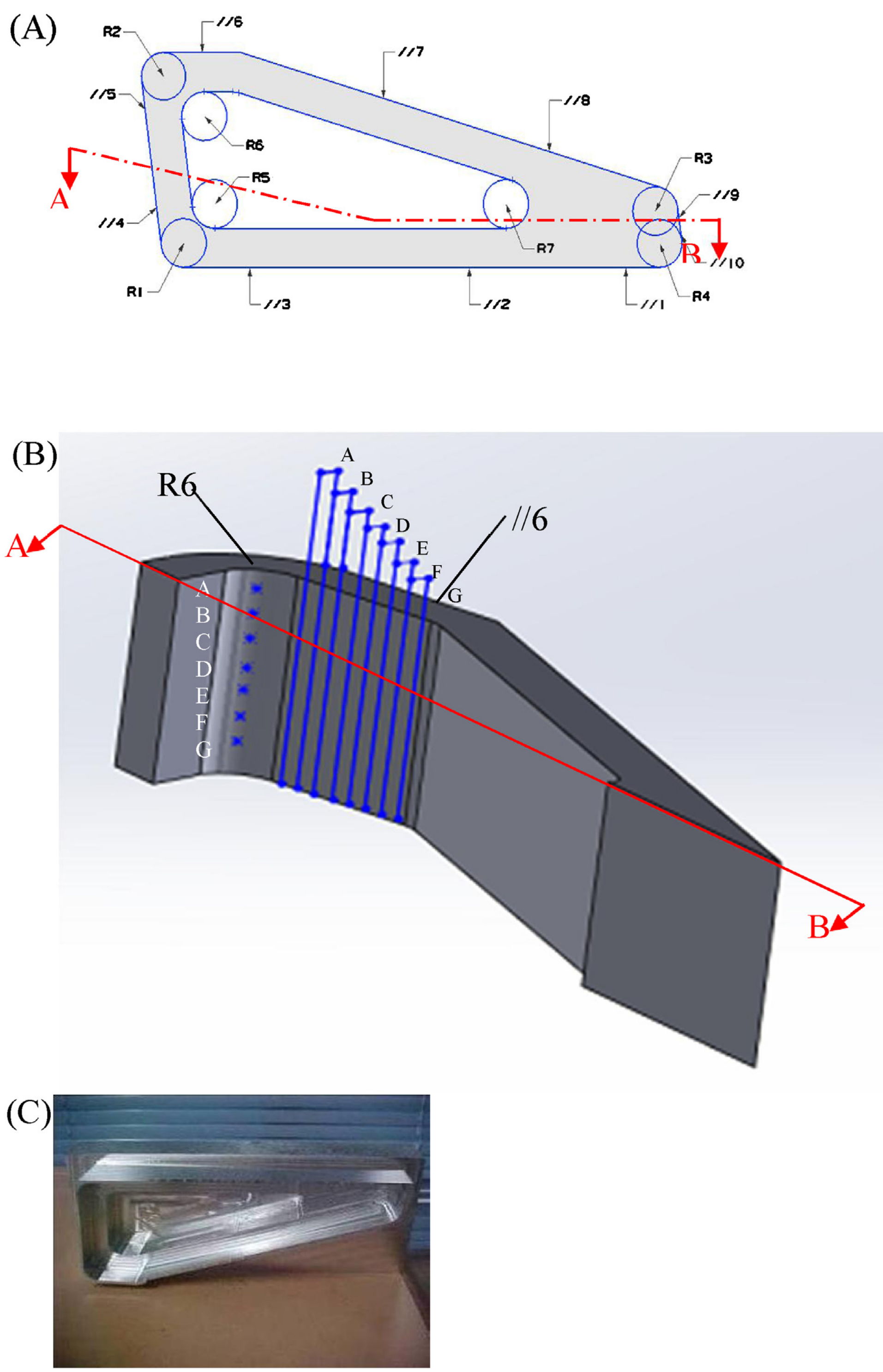


Fig. 2. Points and measurement locations shape errors in the model part. (A) Measurement points of shape errors on the model part and cut AB. (B) Cut AB: 7 measurement positions for mean determination, reference value for evaluation of shape errors. (C) Manufactured model part.

Table 3
Cutting parameters (complex surface).

Operation	Cutting speed, v_c (m/min)	Feed, f_z (mm/tooth)
Thinning	800	0.25
Finishing	800	0.2

aluminum alloy components (norm MEP 08-020 Eng rev B [30]): circularity = + 0.2 mm, diameter [Ø] = + 0.1 mm, rectilinity and parallelism [//] = + 0.01 mm.

Quality evaluation of dimensional and surface of the machined parts was made with a coordinate measure machine (MMC), model

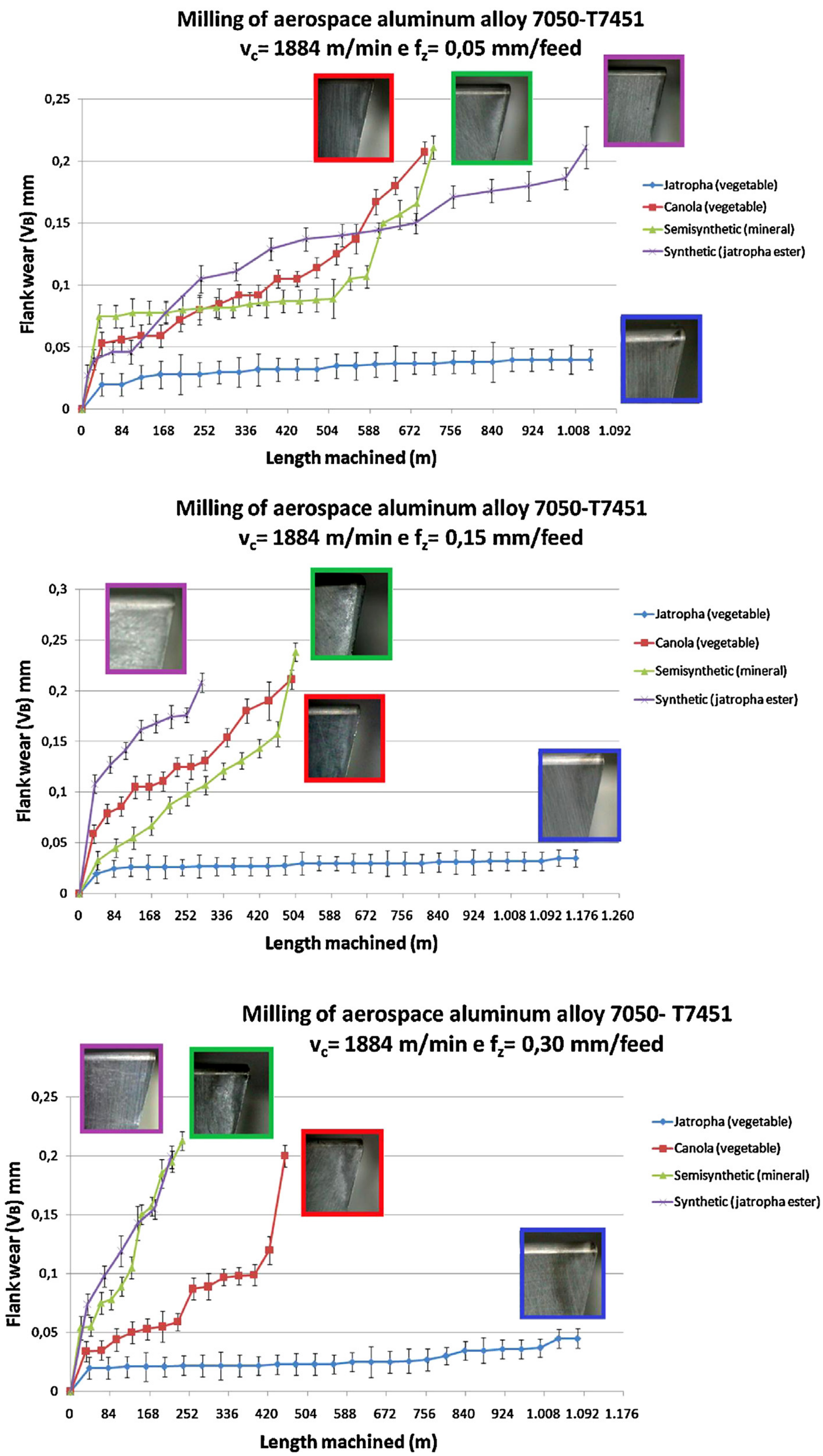


Fig. 3. Tool life with variation of cutting oil and feed rate [f_z] (mm/tooth).

Crystal-Apex C7106, with maximum error possibility of $(1.7 + 3L/1000)$ μm.

The value of the shape errors was measured in two different points distributed along the surface of the model part, as shown in Fig. 2(A). The ratio and diameter are identified by the symbol "R", in the points 1, 2, 3, 4, 5, 6 and 7, and the parallelism and rectilinity, by symbol "//", in the points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11.

In each of these points of measurement, 7 values were measured. Such values, identified by the letters A, B, C, D, E, F and G, were reference to the mean calculus of each point, as shown in Fig. 2(B). This mean value was considered on the evaluation of the results. Fig. 2(C) shows the part model manufactured.

2.2. Chemical characterization of tested cutting fluids

Cutting fluids used in this research were characterized and evaluated by means of the following analyzes:

- Determination of trace metals according to the norms US EPA Method 3052 (Rev.0; 1996) [31] and Method 6010C (Rev.3; 2007) [32] for sample preparation and analyzes respectively.
- Characterization of chemical compounds using Fourier Transform Infrared [FTIR]. In order to get the spectra, samples were analyzed by transmission in equipment Perkin Elmer, Model Spectrum One, spectrum range: 4000 a 650 cm^{-1}, 8 scans, resolution 4 cm^{-1}.
- Determination of crude ash content was carried out in agreement with the norm NBR 9842:2009 [33] (petroleum derived products – crude ash determination). This norm suggests the crude ash determination method in the range of 0.001% a 0.180% of mass, for residual and distillate fuels, gas turbine fuels, crude oils, lubricant oils, paraffin, and other petroleum derived products, in which any ash formation trace is usually considered to be undesirable impurity and/or contaminant.
- The levels of N-nitrosamines in the samples were determined according to method ASTM F1313-90, 2011 [34]. The starting point of this analysis consisted of the extraction of N-nitrosamines with dichloromethane from the oil samples and a further analysis by gas chromatography with the detector TEA.
- Chloride level was analyzed according to the norm ASTM D4208 [35], in which the sample was totally oxidized (burnt) in a calorimetric pump with an oxygen atmosphere and the waste residues of this oxidization were later evaluated with an ion selective electrode so as to qualitatively define the chloride content of the cutting oil samples under study.
- Sample acidity level was determined by the pH indicators (Merck's pH universal indicator tape).
- Evaluation of the foam level of emulsions was based on the norm ASTM D892 [36]. The test was carried out at temperatures 24 ± 3 °C, 93.5 ± 1 °C and 24 ± 3 °C and the measuring result represented the foam volume yielded after air diffusion for 5 min and flow was predetermined by the norm. The test was carried out in three different sequences, as follows. Sequence I: room temperature (24 ± 3 °C), sample of 190 ml in a measuring cylinder with air introduction with the maximum value of 2 kg/cm^2; regulation of air flow from 90 to 97.5 ml/min; set the chronometer at the occurrence of the first air bubbles and wait for 5 min; after 5 min, close the valve and proceed to a reading of foam volume; let it rest for 10 min and read the volume of remaining foam. Sequence II: place the 180 ml sample in a 1000 ml measuring cylinder in a water bath at 93.5 ± 1 °C; after reaching this temperature, follow the steps described in Sequence I. Sequence II: elimination of all foam residue after Sequence II; cool the Sequence II sample to a temperature of 24 ± 3 °C; follow the test as described in Sequence I. Calculus of sequence I, II, or II (ml) = A/B, being A foam volume after 5 min of air diffusion and B foam volume after 10 min of air diffusion.

This characterization verified the physicochemical properties of the cutting fluids being analyzed, their influence upon the machining of aluminum alloy 7050-T7451 and whether they were present in the formulation of cutting fluids that were prohibitive for use in the aeronautical industry. All tests with the cutting fluids, as a standard, used an 8% concentration in the emulsion solution.

3. Results and discussion

In comparison to the other tested soluble cutting fluids, in a machined length of up to 1000 m, the jatropha (vegetable) cutting fluid did not exceed the 0.05 mm value for tool flank wear up [V_B] to the end of the test for the tool life span, as well as on all cutting parameters (Fig. 3), much lower that the stipulated value of $V_B = 0.2$ mm.

Tests for the cutting tool life span showed a higher lubricating power of the jatropha (vegetable) cutting oil. In feed rates [f_z] of 0.15 and 0.30 mm/tooth, cutting tool life [V_B] span was 30% higher than the other cutting fluids under analysis here. It should be emphasized that cutting forces are higher with the increase of feed rate [f_z] and, consequently, the lubricating property of this fluid is the most significant one in comparison to the other fluids. Therefore, the higher performance of the jatropha (vegetable) cutting fluid is pointed up for its lubricating feature and for being a produced from a renewable source.

Souza et al. [37,38] stress in their research the high lubricating properties of vegetable fluids and state that this feature results from the composition of their molecules and from the chemical structure of the fluids themselves. In vegetable-base fluids lubrication is obtained by the intrinsic oiliness of their vegetable components. Ulrich [39] believes that molecules of vegetable-base cutting fluids are long, heavy, and have a bipolar nature with opposing electric polarities. This characteristic makes the droplets of fluid act as small magnets on the metal. This results in a dense and homogeneous alignment of the vegetable-base fluid molecules

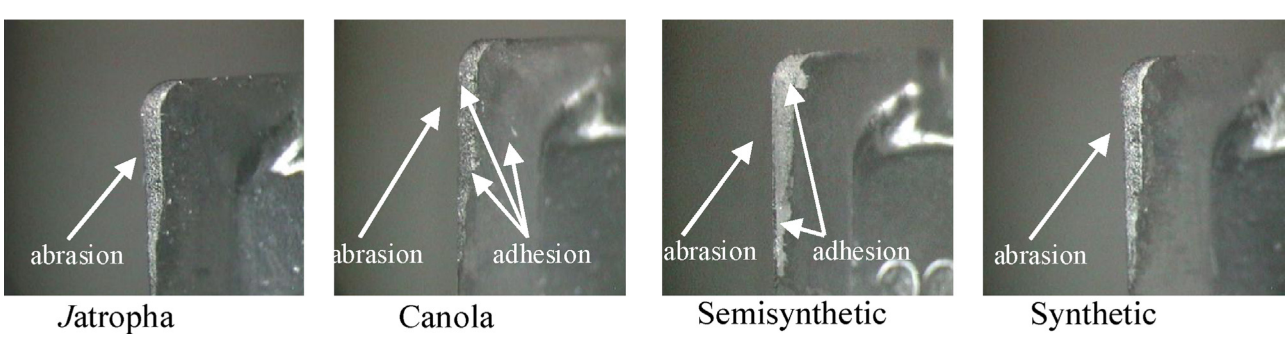


Fig. 4. Cutting tool surface wear outlet.

that is perpendicular to the metal surface, which then generates a lubricant film layer. Such data were confirmed in the test for the cutting fluids life span in which used the vegetable-base jatropha cutting fluid.

It was also observed that the increase in the cutting oil temperature, which was caused by an increase of feed rate [f_z] in the canola (vegetable), semisynthetic (mineral), and synthetic (jatropha ester) cutting fluids constituted an element that reduced significantly the cutting tool life [V_B], so as to typify the unreliability of the lubricant and cooling properties of these fluids. However, it must be pointed out that this situation did not occur when using the jatropha (vegetable) cutting fluid. It was also possible to observe the low level of lubrication of the semisynthetic fluid (mineral) in a quasi-arithmetic scale between feed rate [f_z] and the decrease in machined length by the cutting tool; the increase of cutting temperature [T] decreased in about 250 m the length machined by the tool at each variation of the feed rate [f_z].

Fig. 4 shows that wear mechanism by abrasion was observed in the cutting tool outlet surfaces, for all the cutting fluids and feed rate [f_z] variations. This observation demonstrated a loss of lubricating power and a resulting crater surface wear with the decrease in the machined length performed by the cutting tool (Fig. 4). This type of wear mechanism is manifested in the loss of material by micro grooving or mini-cutting caused by high-resistance chip particles.

Cutting tool wear by abrasion combined with adhesion wear mechanisms was identified in feed rates [f_z] of 0.15 and 0.30 mm/tooth in canola (vegetable) and in semisynthetic (mineral) fluids demonstrating that those fluids are more affected when there an increase in machining temperature [T]. In turn, this increase quickly decreases their lubricating and cooling properties with the occurrence of an increase in the feed rate [f_z]. It is emphasized here that the cutting tool wear mechanism characteristic of the jatropha (vegetable) cutting fluid happens by abrasion, and this can confirm its higher lubricating capacity when compared to the other fluids under analysis.

The mean roughness Ra values found indicate that in none of the cutting parameter combinations with the analyzed cutting fluids the value [Ra] of 3.2 has been exceeded, which is considered a limit value for structured machined aeronautical surfaces (Fig. 5). In relation to the range values for the mean roughness index Ra analyzed here in each cutting fluid, it was found that:

- Jatropha (vegetable): Ra from to 0.075 to 0.10 μm.
- Canola (vegetable): Ra from to 0.10 to 0.15 μm.
- Semisynthetic (mineral): Ra from to 0.10 to 0.12 μm.
- Synthetic (jatropha ester): Ra from to 0.08 to 0.10 μm.

Once again evidence showed that the jatropha fluid had the best lubricating property since both the vegetable-base in natura and the jatropha ester presented the lowest mean roughness index Ra.

According to the norm ISO 3658 [40], the conical helical, arch-shaped, and tangled tubular-shaped forms characterized the chips analyzed here. The radius mean of the chips internal curvature, considering a sample of 20 chips, was found [r] between 2.125 mm and 1.987 mm. The highest chip radius was generated when the jatropha (vegetable) cutting fluid was used, thus, confirming that it had the fittest tribological features (Table 4).

Fig. 6 shows that canola (vegetable) cutting fluid had the highest level of cutting force in comparison to the others measured in this research. This can be explained in agreement with experiments carried out by Gonçalves [13] and Cardoso [41], stating that the double bond (alcohol and CH_2 long chain groups – see Table 5) does not attain the needed resistance for the

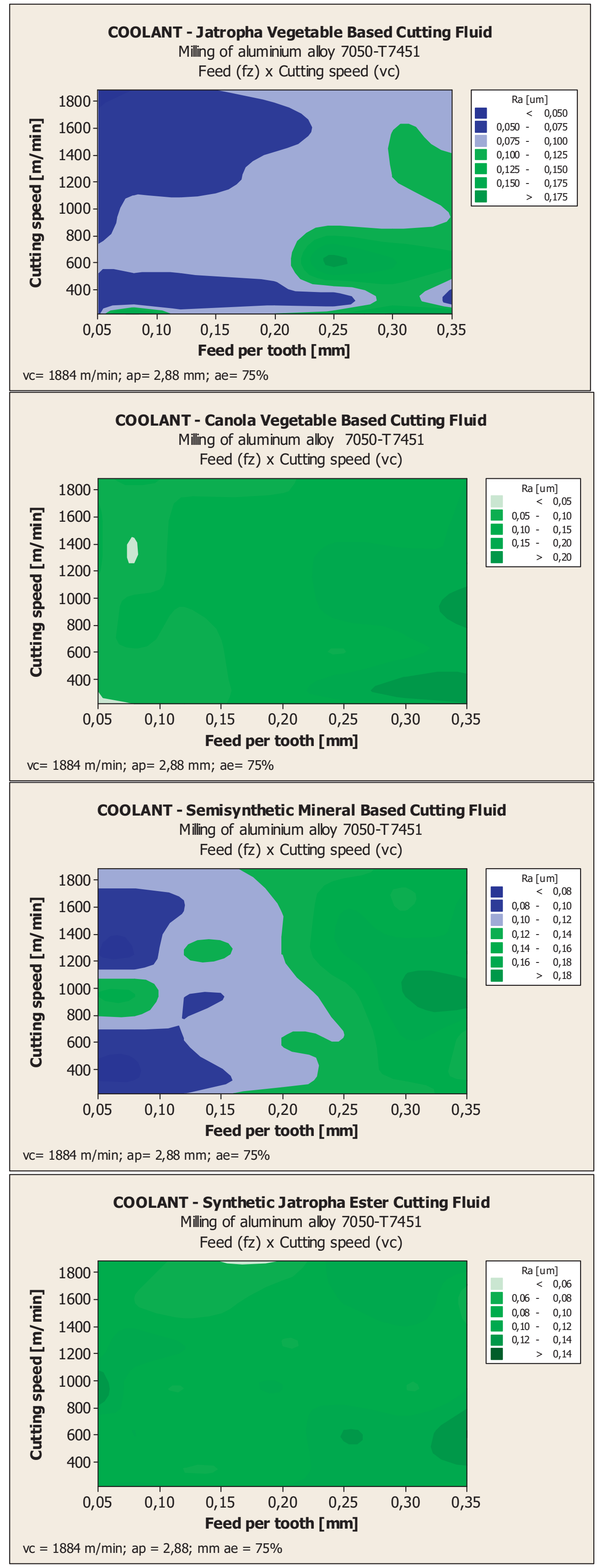
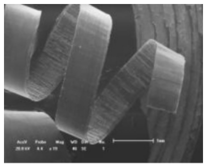
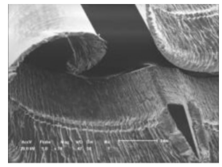
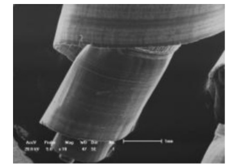


Fig. 5. Mean roughness indexes of machined surface [Ra], measured in cutting parameters (μm).

Table 4
Chip shapes.

Conical helical chip	Arc chip	Tubular tangle chip
		
Predominant shape of jatropha (vegetable) cutting fluid.	Predominant shape of canola (vegetable) cutting fluids, semisynthetic (mineral), and synthetic (jatropha ester).	

lubricating film between tool and part, which is also affected by the increase in the cutting temperature.

The jatropha (vegetable) cutting oil force of presented a very low variation level with the increase of feed rate [f_z], due to its intrinsic oiliness, sulphur content, and its polarity. The low values for the cutting force confirmed its excellent lubricant property.

Fig. 7 presents the shape errors (circularity and diameter) produced in the machining of the model part, with a variation in the cutting fluids and the feed rate [f_z].

Fig. 7 shows that the identification R1, R2, R3, R4, R5, R6 and R7 in the graphic axes show the points were the 7 measurements were taken for mean determination, evaluation reference, as shown in Fig. 2.

With the analyses of the circularity mean, the values found here did not exceed the tolerance limit of 0.2 mm. The highest circularity value observed was 0.073 mm for the canola (vegetable) cutting fluid. Thus, it can be suggested that such a circularity value might have been influenced by the highest level of cutting force achieved by this type of fluid. In relation to the jatropha (vegetable) cutting fluid, it did not present any difference in comparison to the other analyzed cutting fluids, that is, this cutting fluid maintained the same trend in relation to the shape error observed at each measuring point.

As to the mean diameter [Ø] measuring, all cutting fluids remained within the established tolerance limits and they did not show a significant variation in this procedure. The highest identified value was found in the canola (vegetable) cutting fluid that reached the mean value of 20.086 mm for diameter [Ø] measuring. This happened as a result of the cutting force generated by this cutting fluid, as shown in Fig. 6, being the average cutting force [F_c] 35% higher than the other fluids in all the cutting tool life span tests.

Parallelism and rectilinity [//] errors in their relation to the highest mean value measured here demonstrated that there was not a single value higher than 0.009 mm, which was far below the

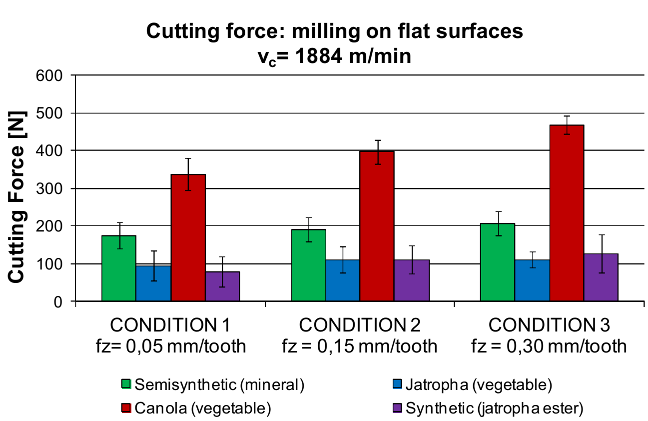


Fig. 6. Cutting force in the flat surfaces milling test.

fixed threshold limit for the manufacturing of aeronautical parts (MEP 08-020 Eng rev B [30]). Therefore, parallelism and rectilinity [//] errors are much less influenced by the lubrication of cutting fluids and much more affected by the cutting tool geometry, as well as by how the cutting tool had been clamped and by the cutting tool cooling system attributes.

Machining tests led to suggest that the jatropha (vegetable) cutting fluid presented more effective results than the other analyzed fluids. Such findings are confirmed by references [13,42–44], who stated that the efficiency of cutting fluids resided in their capability of penetration by capillarity in the secondary shear zone at the interface of chip and tool. Hence, the higher the size and number of unsaturations of the carbonic chain of oil molecules, the better the capillarity effect, in this case, of the vegetable-base fluids.

References [39,45–48] have also stated that the composition of fatty acids is determined by the proportion and position of unsaturations among the carbons. Fatty acid polarity yields guided molecular films that produce oiliness and a wear-resistant property, thus, allowing for a higher level of affinity to metal surfaces. Consequently, vegetable-base cutting fluids are better lubricants than those of mineral-base, and this allows them to be used as a hydrodynamic lubricant. What results from this is a film that inhibits a metal-metal contact as it increases the cutting tool life span. On the other hand, the semisynthetic fluids (mineral base) have a non-polar nature, align themselves randomly at the metal surface, and produce a weaker lubricating layer (Fig. 8).

The presence of significant levels of sulphur in the four samples (Table 5), especially in the one of canola (vegetable) cutting fluid, could be observed in the physicochemical analyzes of cutting fluids. Runge and Duarte [49], states that these sulphur values are related to the use of extreme pressure additives [EP] to improve efficiency in the production process by an increase in the lubricating power. It is emphasized, considering the totality of cutting fluid samples, that sulphur [S] percentage was below the stipulated limit established for use in the aeronautical industry (<4%, norm ASTM D874 [50]), which cannot be considered damaging for machining processes of aeronautical aluminum alloys.

The best machining performance for jatropha (vegetable) cutting fluid can be also evidenced in the physicochemical factors that are present in the cutting fluids under analysis (Table 5).

Results shown in Table 5 suggested that the alcohol-base compound and the CH_2 of canola (vegetable) oil did not offer the stability of film protection between contact surfaces, allowing the chips to adhere to the edge of the cutting tool in cutting conditions of feed rate [f_z] at 0.15 and 0.30 mm/advance tooth (see Fig. 4). They also suggested that the nitrogen–hydrogen [N–H] base compounds of semisynthetic (mineral) and synthetic (jatropha ester) cutting fluids, when combined with the sulphur level, were more resistant than alcohol and CH_2 compounds at high temperatures (Table 5).

Table 5
Percentages of phosphorus, sulphur, and chemical compounds obtained in the absorption test samples.

Samples	Characteristic Absorptions	Sulphur (S) (%)	Phosphorus (P) (%)	Ash levels (%)	Chlorine (Cl) (mg/kg)	Acidity (pH)
Jatropha (vegetable)	Esters, unsaturated aliphatic hydrocarbons (double-linkage), polycyclic/mono-replaceable aromatic hydrocarbons, CH_2 of long chain and linkages N–H.	0.63694	<0.00025[a]	0.38	$<1^2$	8
Canola (vegetable)	Esters, unsaturated aliphatic hydrocarbons (double-bond), alcohol and long chain CH_2 groups/compounds.	1.03177	<0.01954[a]	0.40	$<1^2$	5
Semisynthetic (mineral)	Ester groups, CH_2 of long chain and linkages N–H.	0.79401	<0.00025[a]	0.42	35	8
Synthetic (jatropha ester)	Esters, CH_2 of long chain and linkages N–H.	0.81234	<0.00022[a]	0.44	8	6

[a] Below the level of equipment detection.

It could be verified that the [EP] sulphur [S] additive, which exists in the canola (vegetable) (with a higher amount of this element), the semisynthetic (mineral), and the synthetic (jatropha ester) cutting fluids could surpass the intrinsic lubricating property of the jatropha (vegetable) cutting fluid. The interface temperatures [*T*] might have exceeded 600 °C, which is the working temperature of sulphur [49]. It is stressed that the main reason for the synthetic cutting fluid (jatropha ester) to present lower cutting

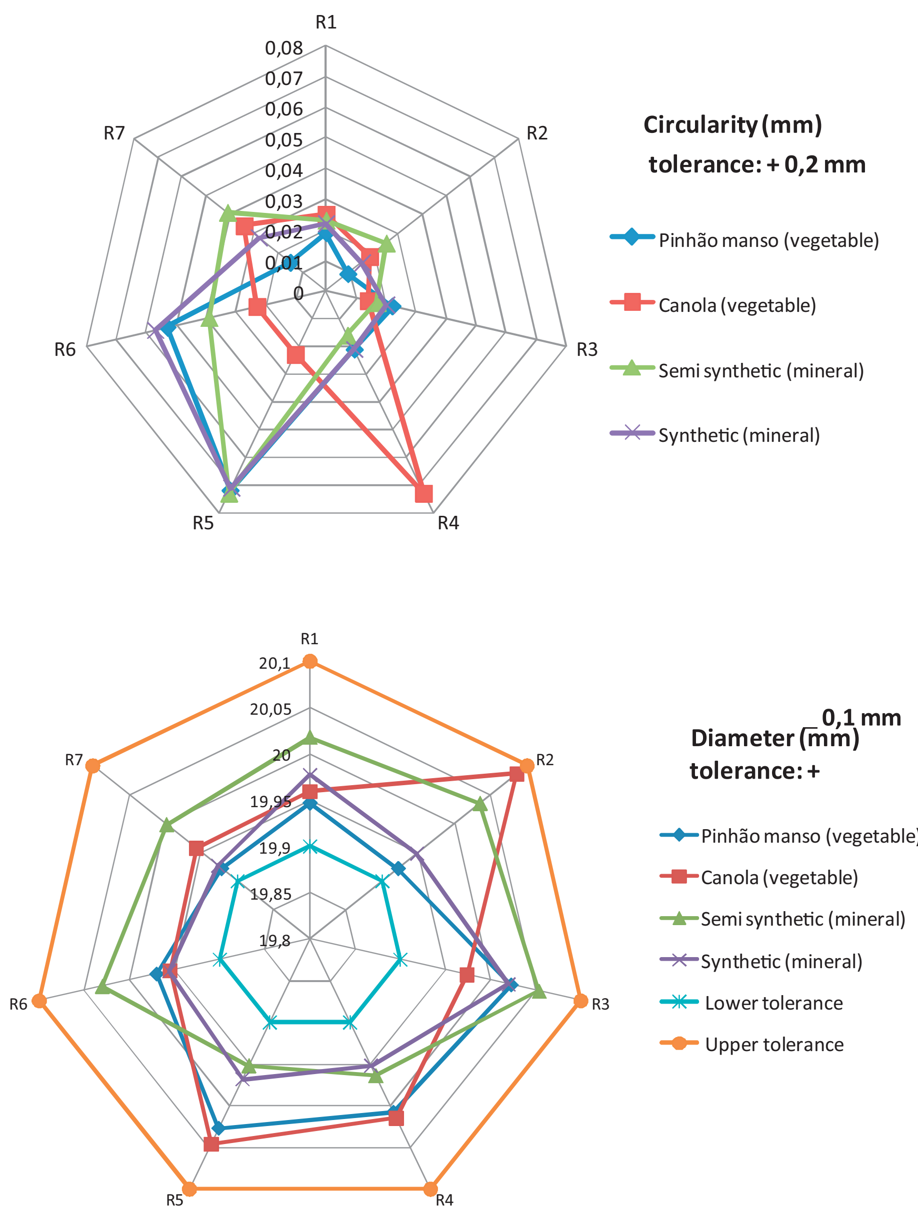


Fig. 7. Circularity and mean diameter values.

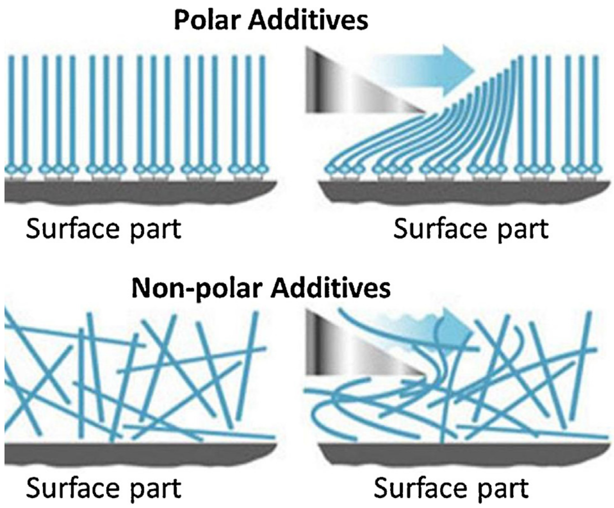


Fig. 8. Alignment scheme of mineral and vegetable oil molecules [43].

force at higher temperatures is the level of sulphur in its compound when combined with the intrinsic lubricity of the fluid itself.

Sulphur efficiency in the composition of cutting fluids was evidenced because of a decrease of 0.018% of sulphur [S], in relation to the semisynthetic fluid (mineral) that caused a significant increase in the cutting force in relation to the synthetic cutting fluid (jatropha ester) of the same compound [N–H] (see Table 5 and Fig. 6).

The reason for a higher force value in the canola (vegetable) cutting fluid might be linked to the alcohol and CH_2 cluster to which it belongs although there has been a higher concentration of the chemical element sulphur. This cluster, in its association to the sulphur concentration, did not allow the formation of a solid lubricant film to adhere to the cutting tool surface so as to avoid the contact between tool and chip. This thin film can be easily broken by any minor contact between tool and machined part, which causes an increase in the cutting force [F_c].

In addition to machinability factors, it is important to appraise peripheral factors, such as cutting fluid maintenance, existence of chemical elements that are restrictive to aeronautical parts and to the operator's occupational health, as well as to the operating conditions of machine and tool in order to avoid foam formation. Hence, by being aware of these factors, more fitting decisions about the use of a cutting fluid in the machining of aeronautical aluminum alloy parts can become easier to take.

Ash levels found in the four cutting fluid samples were considered low (<0.001% of mass), which was not rated undesirable or considered an impurity in the cutting fluids (norm NBR 9842:2009 [33]). As to the level of nitrosamines in these samples, none of the tested fluids presented this chemical element in their composition.

The values shown in Table 5 point out that the semisynthetic (mineral) cutting fluid has in its composition chlorine levels [Cl] that are not allowed by the norm MEP 08-020 Eng rev B [30] (values of maximum acidity index 34 ± 3.0 mg of HCl/g in/of sample), hence its use is not authorized. Jatropha and canola vegetable-base cutting fluids did not present chlorine in their composition.

In relation to acidity, synthetic cutting fluids (jatropha ester) and canola (vegetable) showed higher acidity levels that might inhibit their use in the aeronautical industry so that a possible rectification in the composition of these fluids is required. Foam volumes yielded by vegetable-base cutting fluids (jatropha and canola) were higher than the semisynthetic (mineral) and synthetic (jatropha ester) cutting fluids. Such a finding suggests

Table 6
Foam levels according to norm ASTM D892.

Sample	Sequence I (ml)		Sequence II (ml)		Sequence III (ml)	
	5 min	10 min	5 min	10 min	5 min	10 min
Jatropha (vegetable)	410	300	40	0	360	10
Canola (vegetable)	900	120	500	0	120	0
Semisynthetic (mineral)	170	0	20	0	60	10
Synthetic (jatropha ester)	270	0	0	0	20	0

that this might have occurred because the semisynthetic and synthetic fluids comprise additives that inhibit foam formation (anti-foaming. Synthetic fluid (jatropha ester) displayed the lowest levels of foam formation, in opposition to what is suggested by Filha et al. [15], Stemmer [16], Bressan [51]. Canola (vegetable) cutting fluid was the only one to produce such high a volume of foam that it overflowed the machine reservoir capacity, and the process (Table 6) had to be interrupted. The aeronautical industry has established constraints in relation to the use of anti-foaming and silicon because it affects the paint of machined parts, and it is quite common to have elements such as polymers and alcohol CH_2 compounds in such fluids. The only cutting fluid in which the alcohol compound could be identified was the canola (vegetable), which suggests its lack of efficiency as anti-foaming.

4. Conclusions

Life-span test of cutting tool evidenced the major feature of the jatropha (vegetable) cutting fluid in lubricating property. In all the feed rates [f_z] in the test, it exceeded in about 30% the canola (vegetable), semisynthetic (mineral), and synthetic (jatropha ester) cutting fluids, decreasing with this manufacturing cost by the increase of the cutting tool life span.

As to mean roughness index evaluation, the same trends observed in the canola (vegetable), semisynthetic (mineral), and synthetic (jatropha ester) cutting fluids, with a sudden decrease in roughness index Ra from a starting cutting speed [v_c] of 1571 m/min in all feed rates [f_z]. The values of measured mean roughness indexes Ra for all fluid combinations and cutting parameters remained below the manufacturing floor limit used in the aeronautical industry (3.2 μm) so that their use was approved as a working quality requirement.

Wear mechanisms observed in the cutting tools were those of abrasion and adhesion, above the 0.15 and 0.30 mm/tooth feed rate [f_z], though the influence of temperature upon wear mechanisms was not identified, mostly in relation to flank wear of the cutting tool. Chips identified in the tests showed a tendency to a conical helical shape with the use of jatropha (vegetable) cutting fluid, as well as a trend to a mix of tangled tubular chip in an arch shape for the canola (vegetable), semisynthetic (mineral), and synthetic (jatropha ester) cutting fluids. Such discontinuity in the shape of chips can be explained by the higher lubricating power of the jatropha (vegetable) fluid because, when the lubricating layer yielded by the cutting fluids breaks, the force involved in the contact between the cutting tool edge and the chip increases leading to a discontinuity in the shape of the chip.

The observed cutting forces showed that the canola (vegetable) cutting fluid presented high values for cutting force in all variations of feed rates [f_z]. This suggests that the major reason for this to happen might be the alcohol and CH_2 compound to which this cutting fluid belongs so that it does not guarantee a homogeneous lubricating film on the cutting tool surface, which breaks at the lowest level of contact between tool and part. The jatropha (vegetable) cutting fluid maintained low values for cutting force

[F_c], demonstrating its lubricating property associated to sulphur level (EP additive).

Shape errors did not exceed either the limits established by ruling parameters, and the cutting fluids under analysis for the production of a model part of an aeronautical structure. The cutting fluids of jatropha (vegetable), synthetic (jatropha ester), and semisynthetic (mineral) belong to the cluster of nitrogen and hydrogen [N–H], which has been more effective in maintaining the lubrication property than the cluster alcohol and CH_2 (canola vegetable-base oil). Ash levels in all analyzed cutting fluids remained below the level allowed by the norm NBR 9842:2009 [33].

As to foam formation in machining with the canola (vegetable) cutting fluid, the process had to be interrupted due to the reservoir overflowing so that a new formulation was suggested to be used in such machining process. The jatropha (vegetable) cutting fluid, as well as the other cutting fluids, maintained their low-level foam volumes without hindering both the ongoing process and the quality of the produced surface.

Based on the analysis of levels of chlorine [Cl] and acidity in the cutting oil samples, findings suggest that jatropha (vegetable) fluid stands out because it does not present any chlorine [Cl] element in its composition and does not display any acidity level. The absence of nitrosamines has also to be stressed since they have not been identified in the analyzed cutting fluids. The semisynthetic (mineral) cutting fluid should not be used because of its chlorine [Cl] levels are higher than those allowed by the MEP 08-020 Eng rev B [30] norm. Thus, the efficiency of the use of jatropha (vegetable) cutting fluid has been proven here, according to machining criteria, in relation to the other cutting fluids under analysis. The use of a new product – the jatropha (vegetable) cutting fluid derived from a renewable source – has been shown here as an alternative of sustainability in the production of structured aeronautical parts of aluminum alloys.

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