“A study of the effect of conventional drilling and helical milling in surface quality in titanium Ti-6Al-4V and Ti-6AL-7Nb alloys for medical applications”

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Abstract

In the manufacturing of a medical device, may occur the need to make a hole with a specific function. Among current methods, conventional drilling (CD) referred in this work as drilling (D) and helical milling (HM) are two options with different potential. When making the hole, it is important to choose the most suitable method to obtain the desired geometry and ensure the functionality of the device. This work aims to analyze surface parameters as, arithmetic average height (R_a), the maximum height of the profile (R_t), the average peak to valley height (R_zDIN), chip formation and the geometric deviation of holes obtained by the previously referred manufacturing processes. The specimens, with cylindrical geometry, were made of titanium alloys, Ti-6Al-4V and Ti-6Al-7Nb, currently used in the manufacture of medical devices. For this purpose, holes were made in a machining centre with different feed rate (F) for both methods and in the value of vertical step (a_p) in HM. The results obtained demonstrate that, at lower F and a_p, HM presents better results. The Ti-6Al-7Nb alloy presents better roughness results compared to Ti-6Al-4V, validating it as a material able to be used in medical devices according to the fact that, a lower roughness is associated with higher corrosion resistance and fewer fatigue problems derived from it in components. By the work carried out, can be concluded that the roughness values obtained in HM are lower to those obtained by D making HM as a better option in hole making.

Keywords helical milling, drilling, titanium alloys, medical devices, Ti-6Al-4V, Ti-6Al-7Nb.

1. Introduction

Initially developed for use in the aeronautics industry, it was soon realized that titanium alloys had an enormous potential to be applied in other areas, such as medicine. Titanium alloys have high biocompatibility, high resistance to corrosion and fatigue, low density which makes them a biomaterial of choice for the manufacture of orthopaedic implants, screws, pacemakers, cardiovascular stents.

Its low thermal conductivity, high hardness, adhering particle formation at the cutting edge of the tool and the tendency to harden in the machined zone cause the titanium alloys to be considered difficult to machine [1].

These factors have a clear influence on the final roughness of the machined parts, which has a direct impact on the fatigue strength of the machined parts, as was demonstrated by Sun et al. [2] in his work about the effects of D and HM on titanium alloys. The need to obtain pieces with better surface finish, led to the testing of alternative techniques to D.

Hole making in medical devices is a common manufacturing operation hence the need to use methods that allow to make them efficiently and with the desired quality. A geometric hole in a medical device may assume different functions. It can be used as a previous operation for making a thread, to pass a screw or an electric cable, as a relief of a component’s weight component or even to accommodate a container with slow-release medication or drugs. In order not to compromise the component´s functions, it may be necessary to carefully choose the manufacturing method.

Compared to D, HM offers the economic advantage of being able to drill holes of different diameters with the same tool, the required cutting forces are considerably lower than those of D [3]. Qin et al. [4] concluded that HM cutting force is almost 1/5 compared D cutting force. This also led to a lower generation of high temperatures, a lower probability of occurrence of adhesion of the material to the tool with clear advantages in terms of tool life and less burr both at the entrance and at the exit of the hole, which removes the need for finishing operation such as reaming or countersinking.

Another determining factor for the final quality of the hole, with particular attention to the fact that the materials are admittedly difficult to machine, is the use of cutting fluid during the cutting process. In the work done by Sun et al. [2] the advantage of using refrigeration in the life of the tool is clearly demonstrated. The use of cutting fluid decreases the temperature in the cutting zone due to the lubricating effect that decreases the friction between the tool and the material. The comparison between dry machining, the minimum amount of lubricant (MQL) and abundant lubrication was studied by Qin et al. [5], having come to the conclusion that the use of MQL and abundant lubrication is always preferable over dry machining and that MQL can perfectly replace abundant lubrication with environmental and economic benefits. Li et al. [6] studied the implications of dry machining in tool wear and surface quality in HM.

In its description of the HM process, Liu et al. [7] distinguish the application of HM in two situations, integral D or enlargement of an existing hole. The diameter and geometry of the tool conditions the final result. Milling tools with centre cutting ability should be used, and the cutter diameter should be greater than the radius of the hole to be generated. The optimal ratio between these two parameters is not clear and could be an object of study, nevertheless in an older work on the subject, Tönshoff et al. [8] referred that value of 1.2 as the minimum ratio between tool and hole diameters in order to be able to perform this type of operation successfully.

Cheng et al. [9] studied the use of HM process in micro cutting with flat end mills with diameters inferior than 1mm.

Li et al. [10] concluded that the smaller the ratio of the hole diameter to the tool diameter, the better for its stability with advantages for tool life, however in the work developed by Brinksmeier [11] and Denkena [12] can be verified that a greater ratio between the diameter of the hole to be made and the diameter of the tool, has benefits in tool load since the largest volume of removed material is made by peripherical cutting. Also, if this ratio is close or equal to 1, it’s no longer a situation of HM but D with all the drawbacks associated to it.

Tool wear is a consequence of the severe thermal effects generated in the cutting zone, that, along with the highly chemical reactivity of titanium alloys, promotes a strong adhesion of the material resulting in tool failure [6]. Uddin et al. [13] demonstrated the advantages of using TiAlN tools over uncoated tools in Ti-6Al-4V alloy machining. Sharif et al. [14] conducted a study on Ti-6Al- 4V drilling where coated drill performance outperformed uncoated drills. Zhao et al. [15] concluded that for the same cutting parameters, the tool life of a milling cutter is longer than of a drill in hole-making. A tool that has the ability to maintain its cutting power for longer allows not only greater cost-effectiveness, but also the possibility of guaranteeing the reliability of the process of obtaining the desired geometry.

On a different approach to the HM process, where end mill tool are most used, Olvera et al. [16] conducted a study using ball mil to perform HM with two cutting strategies, and concluded its advantage over D.

Despite not being one of the processes in study in this work, ultrasonic vibration cutting (UCV) [17 – 19] is also a viable option in HM. In UCV, cutting forces are lower, and heat dissipation, material evacuation and chip breakability are improved.

This study intends to compare the effects of both D and HM on titanium alloys Ti-6Al-7Nb and Ti-6Al-4V, both of which are used in the production of medical devices. The effects of the F for both methods and the vertical tool step in HM will be varied as control factors in the experimental planning. The surface quality of the manufactured holes will be evaluated and used as a benchmark.

2. Experimental methodology

2.1 Manufacturing Processes

Brinksmeier et al. [11], Denkena et al. [20] and Tian et al. [21] analyzed comprehensively the theoretical modelling of HM. In the HM process, the rotating tool, a mill with centre cutting, performs a circular motion in the plane XY simultaneously advancing in Z, thereby describing a vertical downward helical movement. The starting position of the milling cutter centre in X or Y must be offset relative to the centre of the hole, this value is dependent on the tool diameter and the hole diameter. The combination of the two movements along with the rotation of the tool causes the cutting of the material resulting in the formation of the hole.

A schematic representation of the two methods can be observed in Fig. 1.

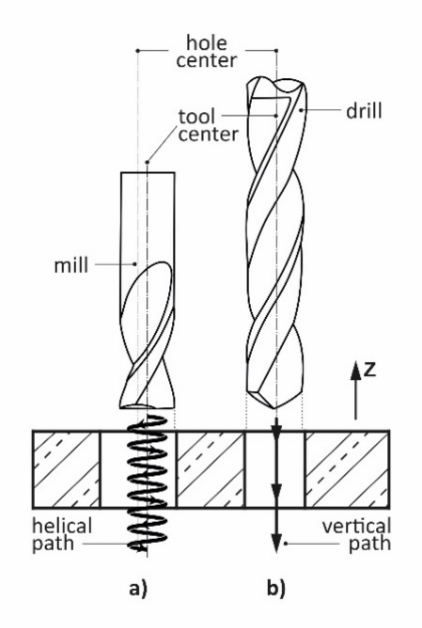


Fig. 1 - Schematic representation of a) helical milling and b) drilling (adapted image from Geier et al. [22])

2.2 Materials

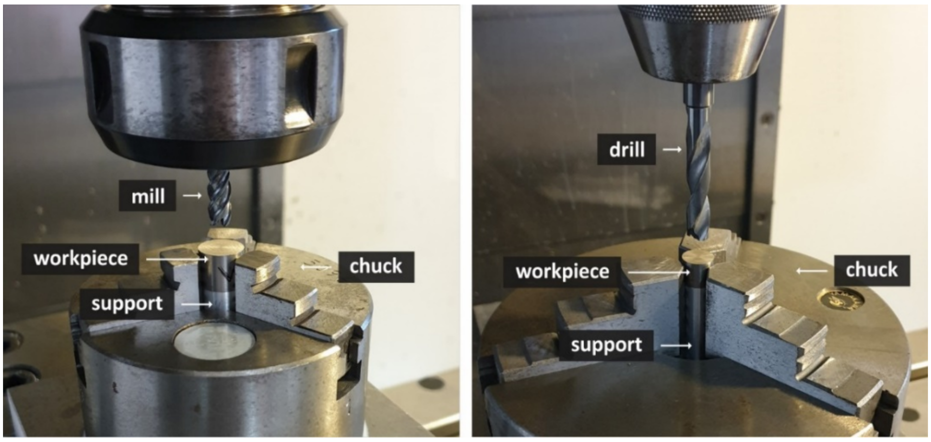
In this study were used two α + β titanium alloys supplied by TiFast Titanium. The Ti-6Al-4V alloy has been the most used in the production of medical devices, however, problems related to toxicity caused by the liberation of vanadium ions have led to the development of new alloys like the Ti-6al-7Nb. Studies developed by Challa et al. [23] demonstrated de reduced toxicity of the titanium alloy with niobium, thus validating its superior biocompatibility. The used test pieces have 12mm in diameter and 10mm in height. Table 1 shows the mechanical properties of the used titanium alloys [24].

Table 1 – Mechanical properties of the used titanium alloys [24].

Material	UTS [MPa]	0.2% YS [MPa]	Elong. [%]	E [GPa]
Ti-6Al-4V	895 - 1110	828 - 970	6 - 18	110
Ti-6Al-7Nb	900 - 1021	800 - 910	10 - 15	105

2.2 Equipment

The equipment used to perform the machining tests was a MIKRON VCE500 machining centre, with 20kW of power, a maximum speed of 6000rpm, a maximum F of 6000mm/min and a FANUC-OM controller. The tests were performed with cutting emulsion at approximately 6%. The experimental setup is shown in Fig. 2. As can be seen, the specimen is tightened in a chuck having an aluminium support underneath to provide support and stability during the test.



a) helical milling b) drilling

Fig .2 - Experimental setup used in tests

2.3 Tools and cutting parameters

For each tool was necessary to consider the cutting speed (Vc) and feed per revolution (fr) in D tests and feed per tooth (fz) in HM tests, so that the tool rotation (S) and feed velocity (Vf) could be determined.

For the D tests, a helical drill with D = 8.5 mm (SD203A-8.5-27-10R1T from SECO Tools) was used for each material and each batch of tests with the following recommended cutting parameter ranges, V_c = [33.7 - 67.2] m/min and f_r = [0.119 - 0.185] mm/rev. For the HM tests, following the same method as in D tests, an end mill cutter with D = 6 mm and 0.3 mm end radius (JHP770060E2R030.0 Z4-SIRA from SECO Tools) was used for each material. The recommended cutting parameters by the supplier for HM cutting are V_c = [88.8 - 114] m/min, f_z = [0.0151 - 0.0451] mm/tooth and a_p = 0.0783 mm. In this case, a_p corresponds to the vertical penetration made by the tool in each step. The wear of the cutting edge of the tool was regularly controlled, considering the variation of average flank wear (VB) equal to 0.3 mm as the possible limit of use, although according to the criteria defined in ISO 8688-2 it can be considered an average value. For each test batch, a new tool was used to eliminate any possibility of the error caused by the wear of tools caused in previous tests. A confirmation test was made for each alloy, method and cutting parameter. So, for HM were conducted 36 tests and 12 for D.

Table 2 presents the cutting parameters for each test for HM and D tests and the estimated operation time for each test. The values of the cutting parameters were chosen taking into account those recommended by the supplier for each tool. An intermediate value, equidistant from the extreme range values, was also considered to understand how the difference in roughness could evolve. As can be seen, apart from the first HM test the average operation time is very similar between the two methods. D tests were made in a single step, so no a_p was to be considered. Also, no center drill was used.

As stated by Bordin et al. [25] F has a major influence in surface quality than V_c. For that reason, V_c was maintained constant for each method so that results could only be influenced by F variations.

Table 2 – Cutting parameters and estimated operation time

Method	**Test (N°.)**	**Vc (m/min)**	**f_z (mm/tooth)**	**Vf (mm/min)**	**a_p (mm)**	**T (mm:ss)**
Helical milling	1	100	0.015	318	0.04	7:24
	2				0.08	3:42
	3				0.12	2:30
	4		0.03	637	0.04	3:42
	5				0.08	1:48
	6				0.12	1:12
	7		0.045	955	0.04	2:30
	8				0.08	1:12
	9				0.12	0:48
Method	**Test (N°.)**	**Vc (m/min)**	**f_r (mm/tooth)**	**Vf (mm/min)**	**a_p (mm)**	**T (mm:ss)**
Drilling	1	50	0.1	375	-	3:50
	2		0.15	562	-	1:33
	3		0.2	749	-	1:55

2.4 Surface roughness tests

Roughness values were measured with a Hommel Tester T1000 roughness tester. For each workpiece, four measurements were carried out on the inside surface of the specimen 90 ° apart from each other to obtain an average value of roughness, and only the intermediate of the four values obtained for each workpiece was considered as valid for the calculation of the average roughness. Also, so that the measurement error was the same, a positioning jig was developed and used to ensure the best possible alignment between the roughness tester and the workpiece. The sampling length was 4.8 mm and the applied cut-off was 0.8 mm

3. Results

3.1 Surface roughness in helical milling

The evaluation of surface roughness can be based on several parameters. The most used are R_a, R_t and R_z, having the last one different definition according to the International ISO system or the German DIN.

R_a is commonly used to characterize or assign a finishing grade (ISO 1302) to a machined surface or about to be machined. The information obtained by R_a can be complemented by R_t and R_z can give more accurate and in-depth information about the machined surface.

Fig. 3 shows the effects of a_p and V_f in R_a for titanium alloys Ti-6Al-7Nb and Ti-6Al-4V in the HM tests. As can be observed, the values for R_a of Ti-6Al-7Nb are generally lower than those of Ti-6Al-4V. This is more pronounced in the case of lower V_f and a_p. The effect of a_p is clear to observe, the increase of R_a is coherent with the increase of a_p, while the change of V_f doesn´t have a pronounced effect.

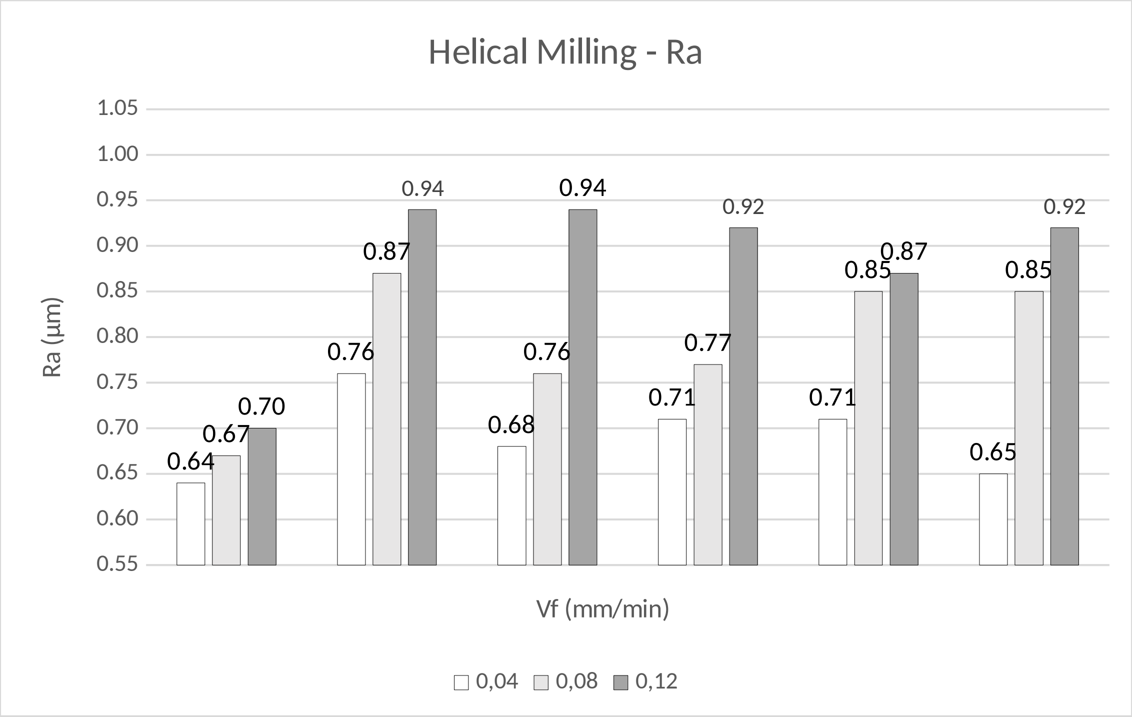


Fig. 3 – Effects of a_p and Vf in R_a in helical milling tests

Fig. 4 shows the effects of a_p and V_f in R_t for titanium alloys in the HM tests. For Ti-6Al-7Nb, results are more regular with a definable pattern than of those of Ti-6Al-4v. It´s clear to see that for lower a_p and V_f the values of R_t are better.

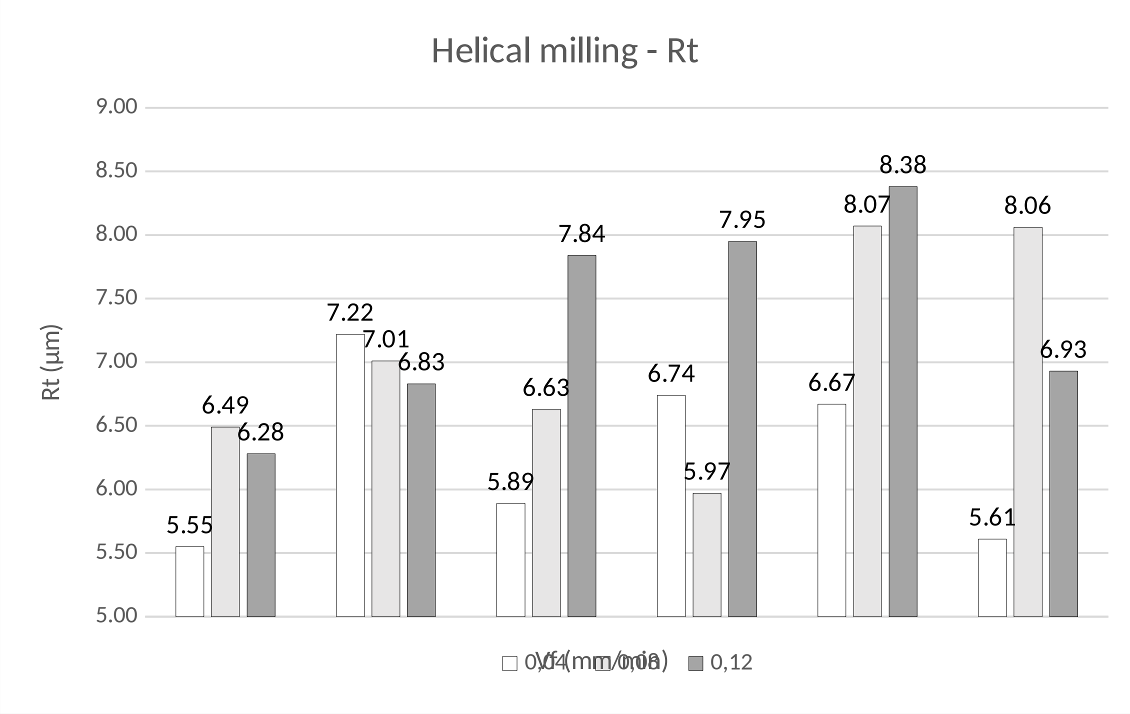


Fig. 4 – Effects of ap and V_f in R_t in helical milling tests

Fig. 5 shows the effects of a_p and V_f in R_z for titanium alloys in the HM tests. Again, as in R_t, results for Ti-6Al-7Nb are clearly patterned, with lower a_p and V_f better roughness can be achieved. Nevertheless, for Ti-6Al-4V results are almost consistent.

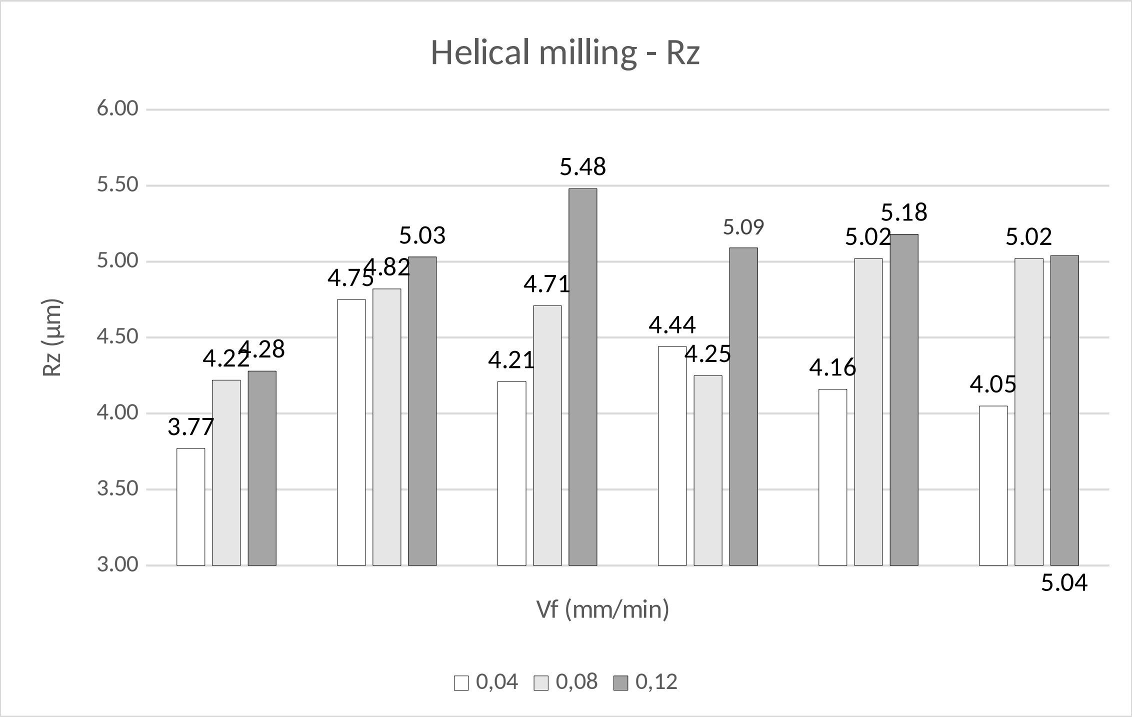
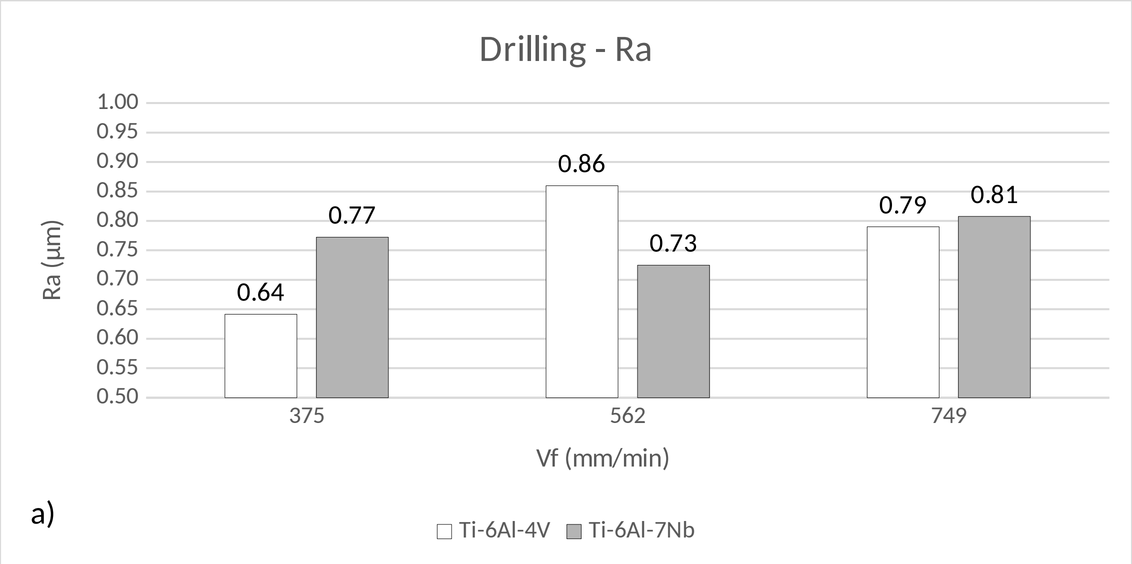
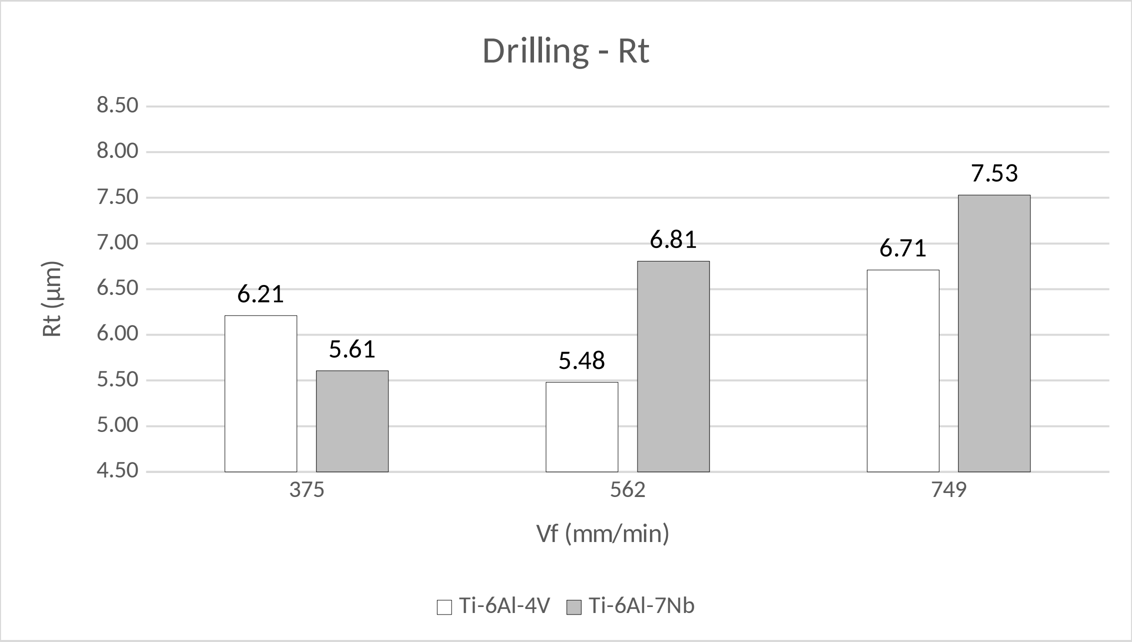


Fig. 5 – Effects of a_p and V_f in R_z in helical milling tests

3.2 Surface roughness in drilling

Figure 6 shows the effects of V_f for titanium alloys in the roughness parameters chosen: R_a, R_t and R_z. What somehow stands out is the similarity of measured results for R_a and R_z, where there is clear consistency in the case of Ti-6Al-4V alloy, and the same for R_t in the case of Ti-6Al-7Nb alloy. As in the case of HM, the lowest values of roughness generally correspond to the lowest values of V_f.





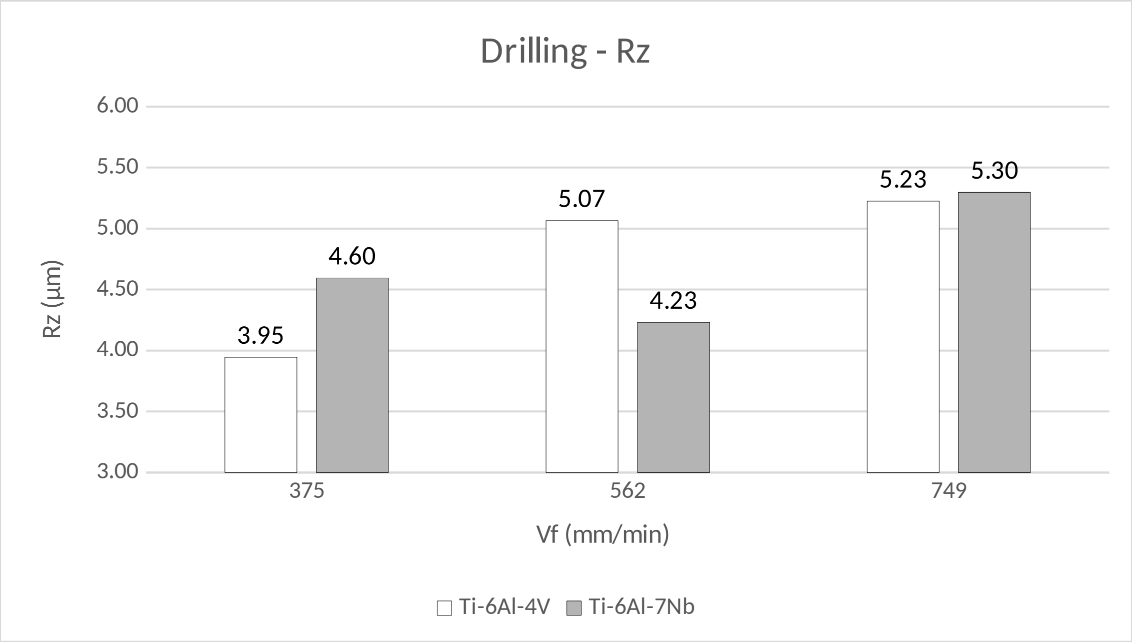


Fig. 6 – Effects of V_f in a) R_a, b) R_t and c) R_z for drilling

3.3 Chip formation

As expected, the chips produced in each type of operation were different, as was demonstrated by Qin et al. [4] and [1]. The chips produced by the HM can be described as arc chips and loose, and those obtained by D can be described as conical helical chips varying between long and short (Fig. 7). Also, in HM tests, it is possible to verify the formation of a flat cap resulting from the gradual and progressive movement of the milling cutter. This was also found in some of the D tests but with a conical shape.

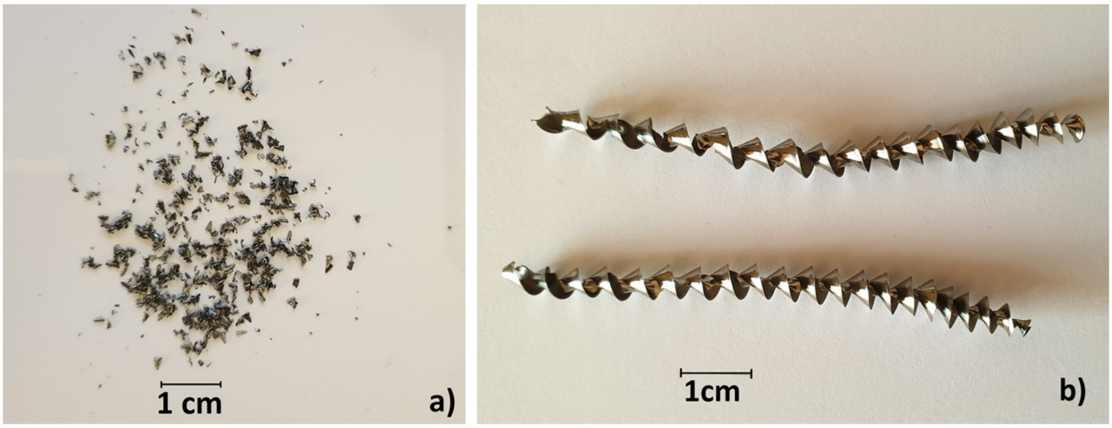


Fig. 7 – Chip formation for each type of operation: a) helical milling, b) drilling

The chip formation is directly related to the dynamics of the process that gives origin to it. In HM, the contact of the cutting edge of the tool with the material is intermittent causing an interrupted cut, which results in small flakes of material. In D, however, the contact of the cutting edge is permanent and always compressing downward the material forming long spirals along with the rotation of the tool.

From a mechanical production point of view, the chips from HM present advantages since are easy to remove from the working zone causing less harm to the surface.

3.4 Tool wear and geometric deviation of the holes

Every tool was measured before their tests batch to confirm their nominal dimension. After the tests were made, all tools were measured again and had the same wear of 0,03 mm, both for mills and 0,02 mm for drills. This means that both Ti alloys induce similar wear to both tools. The measurements were made using an exterior Mitutoyo© micrometre with 0.01 mm resolution.

Concerning geometric deviation, test samples were measured at the entrance and exit of the hole machined or drilled. This was made to confirm the existence of dimensional deviations caused by deflection of the tool in the case of HM, or tool wear. To perform the measurements, a Mitutoyo MT microscope with 0.001 mm resolution was used. For each value presented, two measurements apart 180° was made, thus constituting the average value of the measurement.

For comparison purposes, only the most apart test samples were measured, the one with the lowest a_p and V_f, and the one with the highest a_p and V_f.

Results show that in HM there was a decrease in the diameter of 0,05 mm for Ti-6Al-7Nb in the first test sample and 0,02 mm in last test sample. Also, the top diameter of the first test sample and the bottom diameter of the last test sample were compared and a 0,11 mm difference was recorded. It was also verified that between the first test sample and the last sample there was a difference of 0,11 mm.

Also, in HM, but for ti-6Al-4V alloy, results were very similar: 0,03 mm for the first sample and 0,01 mm in the last sample. The difference between the top of the first test sample and the bottom of the last test samples was 0,1 mm. Very similar to the value measured in Ti-6Al-7Nb alloy.

In D tests, results were very consistent in both alloys, with a decrease of 0,02 mm from beginning to end. This value was coherent with the wear measured in drills after tests were made.

4. Discussion

This work aimed to evaluate the difference in terms of roughness, chip formation and dimensional deviation in holes obtained through two fabrication methods, D and HM in two titanium alloys currently used in the production of medical devices.

Considering the R_a parameter, the roughness values measured in both methods ranged from 0.6 to 0.95 μm, these means that they varied from N6 to N7 grades. Huang et al. [26] concluded that a surface roughness of 0.05 to 1.2 μm can be an important factor to cell adhesion. This means that components obtained by these methods and with the parameters used in the performed machining tests may be used or considered for medical applications such as an orthopaedic implant.

It should be taken into account that all tests were carried out with tools chosen specifically to work with titanium alloys. This was intended to minimize the well-documented impact on the difficulty of machining titanium alloys.

Comparing the obtained values by the two methods, although they were performed with different cutting parameters but still within those recommended by the manufacturer, they are quite similar. Should be considered to perform tests with identical parameters so that this comparison could be more accurate.

As with HM, in D the roughness values of Ti-6Al-7Nb tests are in a general, lower than of those of Ti-6Al-4V. Considering roughness as a condition that can be used to define the degree of biocompatibility of a manufactured component, then the Ti-6Al-7Nb alloy that was developed to minimize the proven toxicity problems related with Vanadium, also proved to be more biocompatible in manufacturing processes. Nevertheless, roughness values for Ti-6Al-4V seem to be uniform with consequent lower standard deviation.

Should also be considered in the process of choosing the most adequate method of hole making, the cost of the tools and the task execution time. The tools used in HM were almost 30% of the value of the drills used, with the advantage of flexibility in getting the desired dimension, as was stated by Ozturk et al. [27] and Tian et al. [21]. Concerning manufacturing times, D has a clear advantage in mass production, but in small batches of parts, with the right cutting parameters, HM can be as profitable as D. For example, in the case of manufacturing orthopaedic or orthodontic implants, where the customization of the product according to the patient's image is becoming increasingly important, where immediate and non-standard solutions need to be used, then HM, due to the versatility shown in obtaining different geometries with the same tool, assumes an important role.

Although it is mentioned in the literature a few considerations about the relation between the tool and hole diameters, this theme could benefit of a more in-depth study, so that a more quantifiable and optimal relation could be obtained. This relationship will influence the final result obtained, both in the roughness and in the dimensional deviation of the hole motivated by the necessary effort to be developed by the tool. The optimal relation between tool diameter and a_p can also be studied so that it can be standardized to obtain a desirable result.

Tool deviation is related to the behaviour of the tool as it moves against the material to be removed. At the beginning of the cut, the tool adopts a compression behaviour, in the end, as the material upfront begins to become scarce it tends to adopt a tractive behaviour, and it’s almost obliged to be directed to the most fragile zone of the sample, that is precisely in the centre. To understand this difference in values, the tool wear caused by the number of tests performed must be taken into account, along with changing the cutting parameters which were progressively more demanding for the tool. These factors influence the radial forces during the cut leading to a deflection in the cutter resulting in the deviation of the desired dimension. For general work, this issue will not have much influence, but in components where there is a need for greater dimensional accuracy, this is a problem that will necessarily have to be addressed.

The manufacturing potential of a mill, that allows different geometries to be obtained against the single geometry operation allowed by a drill, and its cost, that is about lower than half of a drill, makes HM to have an advantage over D. Taking all this into account and considering that the roughness values obtained in HM are close to those obtained by D, HM presents itself as a better option in hole making, this is consistent with the work conducted by Sun et al. [2] and Barman et al. [1].

5. Conclusions

In this work, it could be possible to evaluate and compare two different hole making methods, HM and D applied to two Ti alloys currently used in medical devices manufacturing**.** Not only the performance of two manufacturing methods was analysed, but also the influence of different cutting parameters on the tested materials. Concerning to the tested titanium alloys, Ti-6Al-4V and Ti-6Al-7Nb, from the results obtained can be observed that the roughness values for the three parameters considered, R_a, R_t and R_z, are very similar between the two alloys. However, for lower F in the HM, the alloy Ti-6Al-7Nb clearly presents lower roughness values, meaning that this alloy has better machinability than the Ti-6Al-4V alloy for those cutting parameters. By the machining tests carried out and considering that this alloy was developed to overcome the toxicity issues raised by the presence of Vanadium, the Ti-6Al-7Nb confirms its adequacy to be considered as a valid alternative to the Ti-6Al-4V.

The major conclusions of this work are summarized as follows:

- Cutting parameters are clearly an influencing factor in R_a, R_t and R_z values. Lower V_f and a_p results in better roughness values;

- In Ra measurements, HM a_p has a clear influence on surface quality while V_f is more discrete;
- Considering roughness values, R_a, R_t and R_z, as a comparison term, then HM presents a more valid option than D;
- The titanium alloy Ti-6Al-7Nb presents lower roughness values for lower V_f and a_p compared to the Ti-6Al-4V alloy.

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