Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 December 2018 doi:10.20944/preprints201812.0013.v1

Peer-reviewed version available at *J. Manuf. Mater. Process.* **2018**, *2*, 82; doi:10.3390/jmmp2040082

Article

Flexible abrasive tools for deburring and finishing of holes in superalloys

Adrián Rodríguez [1], Asier Fernández [2], Luís Norberto López de Lacalle [3] and Leonardo Sastoque Pinilla [4]*.

[1] Aeronautics Advanced Manufacturing Center, Zamudio 48170, Spain; Adrian.Rodriguez@ehu.eus
[2] Aeronautics Advanced Manufacturing Center, Zamudio 48170, Spain; Asier.Fernandez@ehu.eus
[3] Aeronautics Advanced Manufacturing Center, Zamudio 48170, Spain; Norberto.lzlacalle@ehu.eus
[4] Aeronautics Advanced Manufacturing Center, Zamudio 48170, Spain; EdwarLeonardo.Sastoque@ehu.eus; Corresponding author.
* Correspondence: cfaa2015@ehu.eus; Tel.: +34 688 673 836

Abstract: Many manufacturing sectors require high surface finishing. After machining operations such as milling or drilling, undesirable burrs or insufficient edge finishing may be generated. For decades, many finishing processes have been handmade-basis; this fact is accentuated when dealing with complex geometries especially for high value-added parts.

In recent years, it's a tendency of trying to automate as far as possible this kind of processes, repeatability and time/money savings are main purposes. Based on that idea, the aim of this work is to check new tools and strategies for finishing aeronautical parts, especially critical engine parts made on Inconel 718, a very ductile nickel alloy. Automating edge finishing of chamfered holes is a complicated but really important goal.

In this paper, flexible abrasive tools were used for this purpose. A complete study of different abrasive possibilities was carried out, mainly focusing on roughness analysis and final edge results obtained.

Keywords: Flexible abrasive tools; finishing; rounding edge; superalloys.

1. Introduction

Titanium alloys and nickel-base superalloys are widely used today in aerospace components, commonly used in engines, considering that superalloys and concretely Inconel 718 are capable of working in corrosive environment and high temperatures. Those materials can be used as part of gas turbine engines, steam, nuclear components, chemicals, etc. There is a strong demand on dimensional accuracy and surface roughness for these high-value components.

Drilling holes in aerospace components is often a delicate operation, the hole amplifies the stress around it by a factor of two [1]. Moreover, it is often the last machining operation, with a looming risk of making a scarp part due to a single bad hole. This circumstance determines the final time used in the production of the part, and a lack of quality can guide to its rejection, having to be especially taken into account the reliability of the process due to the costs already involved. Therefore, it is a high value-added operation [2].

Currently in industrial practice, drilling process are widely used due to its versatility and the short time invested in performing the task. However, these operations produces results with not very high quality so it is required complementary operations such as dotted, re-drilling, reaming, chamfering and edge finishing. This fact supposes a waste of time, both in subsequent cutting processes and in tool changes. The "not very high quality" refers, basically, to the deviations that occur in terms of diameter tolerances, surface roughness and burr formation; inherent phenomenon

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 December 2018 doi:10.20944/preprints201812.0013.v1

Peer-reviewed version available at *J. Manuf. Mater. Process.* **2018**, *2*, 82; doi:10.3390/jmmp2040082

in the process. Also, the effect of cutting parameters on the hole quality (circularity and hole diameter) and tool wear during the drilling of super alloy Inconel 718 allowed to infer that cutting speed and feed rate played a great role in the variation of deviation from circularity values. [3]. The available literature regarding drilling on high strength materials is rather limited [4,5]. However, in recent years there were further investigations in new techniques and processes to drill holes on these alloys.

Among these new techniques, ultrasonic assisted machining is one of the most used. This is a machining technology where a high frequency vibration (20kHz) with amplitude around 10μm, overlaps the continuous movement of the cutting tool, providing an output power between 50W and 3000W [6]. The use of ultrasonic-assisted processes allows a reduction in cutting forces by 30-50% [7], an improvement of the final surface quality, better chip evacuation and a longer tool life [8].

Other authors propose alternatives to traditional drilling. The idea is to use a ball-end milling tool giving it a helical motion around the hole. Regarding the helical milling, there are two similar helical milling techniques: Ball Helical Milling (BHM) and Contouring Ball Helical Milling (CBHM) [9]; results were quite good in quality but times were far from those obtained in twist-drilling operation, or in other processes [10-11] *Takt-time* in aeroengine manufacturing prevent in many cases to replace the drilling with twist drills, so edge burrs and not very good finishing are common issues. In emerging processes, the plasticity of metal is also key, as shown in [12-13]

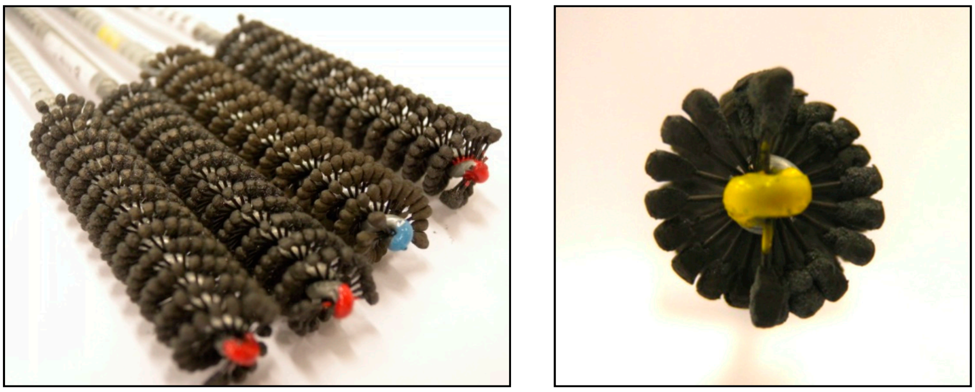
In this paper, brushing techniques using abrasive flexible tools are studied. The aim is to implement these tools for the finishing process, being able to improve the surface finish obtained on one hand, and get the rounding of edges in countersunk holes on the other. Flexible hone tools are available in Silicon Carbide, Aluminum oxide, Zirconia Alumina, Boron Carbide, Tungsten carbide and even in other grades, with diameter ranging from 4 to 1000 mm.

In this work, different tools available in the state of art are presented. Tests were carried out in order to make a first approach to the use of these tools, with interesting results are shown below.

2. Flexible abrasive tools

Companies such as Brush Research Manufacturing (BRM) have a long history of solving difficult finishing problems with brushing technology. The term "brush" is commonly associated to the classic twisted wire brushes or the nylon ones used for deburring or edge blending. It is a flexible and elastic abrasive tool, ideal for soft cutting in finishing operations, "plateau honing", cylinder liners deburring, hydraulic and pneumatic components, as well as other industry sectors such as aeronautics, automotive parts, screw machining, etc.

Those are a general-purpose tools (Figure 1) which versatility stems from the small abrasive balls overlapped at the end of a nylon filament. Each ball is independent of the others; this fact ensures the centering and auto-alignment with the hole. Having complete control of process parameters and identifying and assessing the influence on the final surface is essential for an efficient implementation of these tools in CNC machines and robots.



(a) (b)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 December 2018 doi:10.20944/preprints201812.0013.v1

Peer-reviewed version available at J. Manuf. Mater. Process. 2018, 2, 82; doi:10.3390/jmmp2040082

Figure 1. (a) Tools with different abrasive qualities. (b) Tool detail (3x).

One application of these flexible tools is the surface finishing and the edge blending of holes made in aeronautic alloys, such as Inconel 718 and Ti6Al4V. A wide range of abrasives and grit sizes are offered by BRM and other companies. This implies the necessity to carry out a comparison between the different abrasive grades. Tests' results of different abrasive types and grain sizes are presented in this work. The parameter measured in this first approach is the final roughness of the brushed holes. Table 1 shows the variety of tools used. (Prices are shown because in some cases are double than other solutions.)

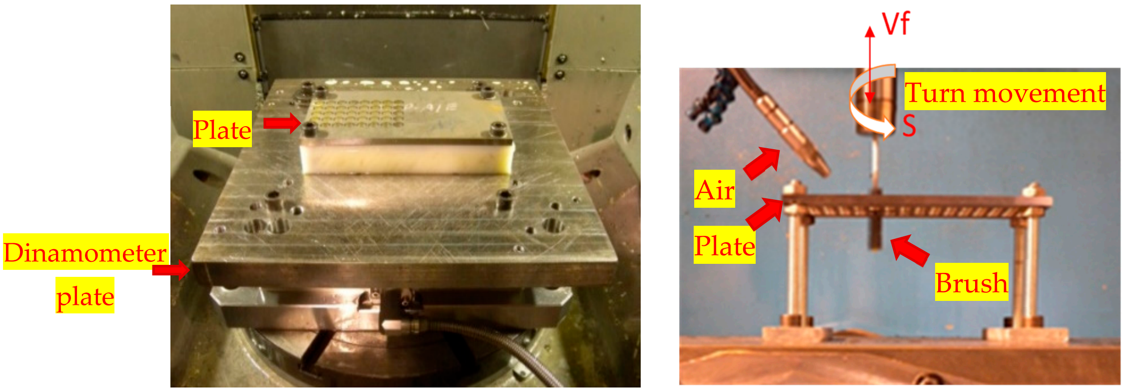
Table 1. Different flexible abrasive tools used in tests.

Code	Abrasive	Grit Sizes	Nominal diameter	Web Price
SC10	Silicon Carbide	180	10mm	≈ 12 $/un
SC11	Silicon Carbide	180	11mm	≈ 12 $/un
SC11 - 400	Silicon Carbide	400	11mm	≈ 23 $/un
BC11	Boron Carbide	180	11mm	≈ 15 $/un
Di11	Diamond	2500 C Mesh	11mm	≈ 30 $/un

3. Previous tests on Ti6Al4V alloy

Preliminary tests on Ti6Al4V alloy were carried out. This alloy was used firstly because is more economical, easier to buy and with better machinability than the superalloys, such as Inconel 718. Titanium plates were used (200x100x7.5mm dimensions); the main aim of these tests is to stablish a first approach to the process before doing it in Inconel 718. On the other hand, titanium alloys are used not only in engines but in airframe key parts, which are joining the wings to the airplane body.

Prior to conducting the brushing tests, 80 holes with 10.7mm diameter were drilled on the plates. The following conditions are used in previous drilling: Vc = 35m/min and f = 0.12mm/rev. Figure 2 shows the experimental set-up.



(a) (b)

Figure 2. (a) Drilling Set-up. (b) Brushing Set-up.

As shown in Figure 1 and gathered in Table 1, five different flexible abrasive tools were used. With each different brush, 16 holes have been made at these brushing conditions: Vc = 60m/min and f = 0.5mm/rev. Figure 3 shows the results of roughness measurement, both drilled holes and the brushed ones. Firstly, the surface quality obtained in previous drilling with the conditions used is quite good, averaging around 0.5µm Ra. The main problem is the results dispersion, varying the Ra roughness parameters from 0.29µm to 1.17µm.

After brushing with the five different flexible abrasive tools, the roughness parameters decreased and the results dispersion is lower. The best brush type for this material in terms of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 December 2018 doi:10.20944/preprints201812.0013.v1

Peer-reviewed version available at J. Manuf. Mater. Process. 2018, 2, 82; doi:10.3390/jmmp2040082

surface roughness is the SC11-400, as it reduces the average Ra roughness up to 0.25µm, with values between 0.2µm and 0.3µm. (Figure 3).

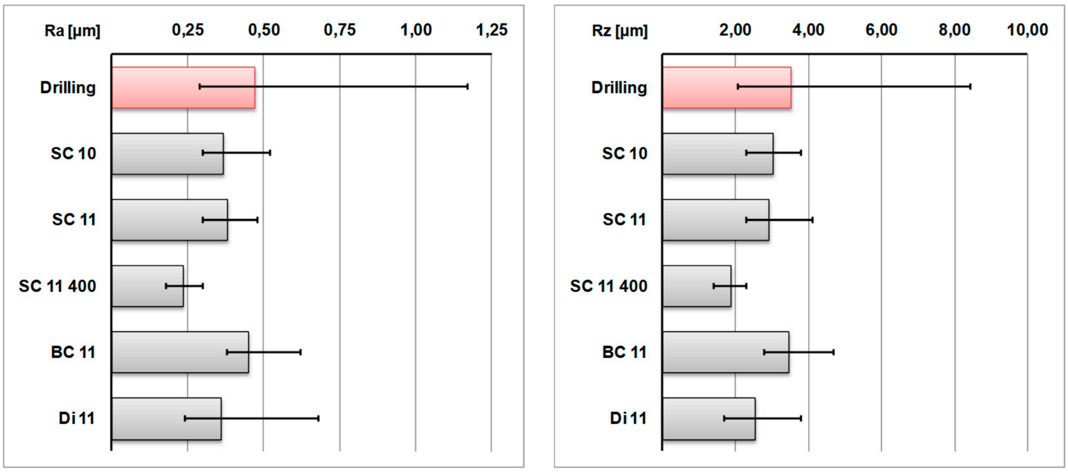


Figure 3. Ra [µm] and Rz [µm] roughness values after drilling and after finishing Ti6Al4V

4. Test on Inconel 718 superalloy

Basing on data from preliminary tests carried out on Ti6Al4V, it is known that the five different flexible abrasive brushes were able to reduce the roughness parameters. Moreover, it is an easy and economical finishing process that can be carried out in machine tools.

On the other hand, preliminary tests show a low cutting capacity. It is difficult to make a chamfer on a hole or deal with large burrs because removing that much material is impossible. However, these brushes could be useful in order to finishing surfaces, rounding edges or cross-hole deburring [9]. For these reasons, experimental tests were carried out on Inconel 718 plates, which is a commonly used material in aerospace components working at high temperatures. This is a difficult material to machine, so the soft cut of these brushes may be insufficient.

In this case, Inconel 718 plates were used: 200x100x7.5mm dimensions, similar to those used in preliminary tests in Titanium. The tests were carried out in an Ibarmia ZV25 milling machine, with a spindle with 25 KWs. Regarding the previous drilling, the Table 2 shows two different conditions used.

Table 2. Conditions used drilling Inconel 718

	Vc [m/min]	f [mm/rev]	S [rpm]	Vf [mm/min]	No. Holes
"A" Conditions	20	0.06	595	35.7	40
"B" Conditions	25	0.06	744	44.6	40

4.1. "A" Conditions.

Two different cutting conditions in previous drilling in Inconel 718 were tested. The first conditions are established by the tool manufacturer, the second ones are rather demanding in order to reduce processing time and increase productivity. The aim is to compare the surface roughness results after brushing. The drilling parameters in "A" conditions are c = 20m/min and f = 0.06mm/rev.

After performing the drilling, brushing tests were carried out. In this case the same brushing conditions as in preliminary test have been used (Vc = 60m/min and f = 0.5mm/rev).

Figure 4 shows roughness results obtained before and after brushing. The surface roughness obtained after drilling is moderately good (around 0.5µm Ra) thanks to the conservative drilling conditions used. After brushing, the results show that the roughness values decrease somewhat, but not significantly. In the case of SC10 brush, the roughness becomes worse. This implies that for this material and using the drilling conditions given by the manufacturer, these SC10 brushes are not suitable. As for the rest of the tests, like what happened in Titanium, the best roughness results are achieved with SC11-400 brushes. However, BC11 brush provides similar roughness values and less

 doi:10.20944/preprints201812.0013.v1

Peer-reviewed version available at *J. Manuf. Mater. Process.* **2018**, *2*, 82; doi:10.3390/jmmp2040082

deviation in the results. In addition, BC11 brushes are cheaper and with less wear after brushing than SC11-400, so BC11 is the most suitable in this case.

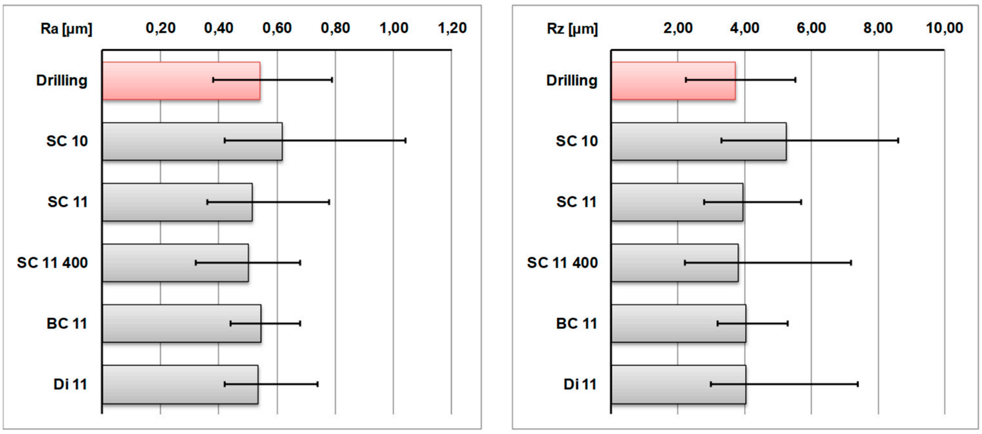


Figure 4. Ra [µm] and Rz [µm] roughness values after drilling and after finishing Inconel718

The results obtained in this case also show that using these drilling conditions it is too unproductive to execute a brushing operation because the surface improvement is roughly inappreciable. In the following section, the brushing process in more demanding drilling conditions is examined. In this case, the brushing process could be useful.

4.2. "B" Conditions.

In this section, the previous drilling conditions are: Vc = 25m/min and f = 0.06mm/rev. In this way, the roughness results obtained after drilling were worse than in previous cases. However, brushing could be useful in this case. Figure 5 show roughness results. The roughness values observed before brushing were around Ra 0.9µm, with a large dispersion of results. After brushing, the roughness parameters decreased to values lower than 0.65µm Ra. In this case, BC11 brush provided the lowest roughness values and the lowest deviation of the results, so this was the most convenient. Besides, the tool wear was not critical in this case.

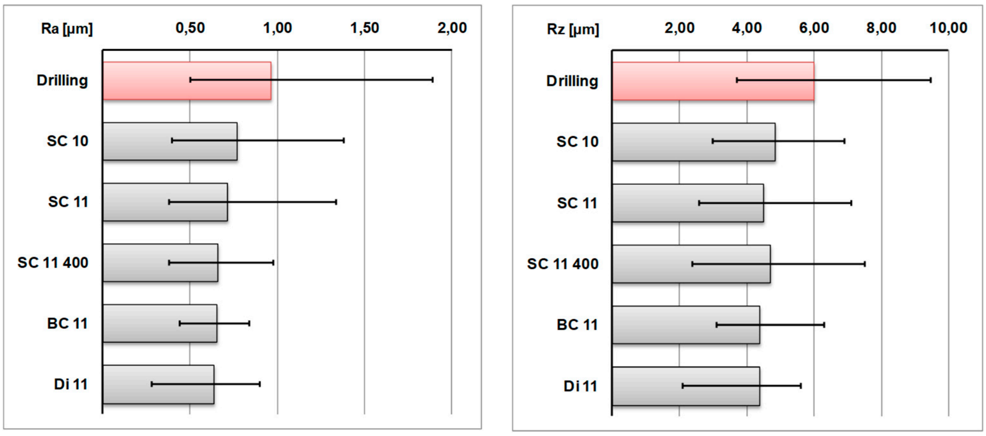
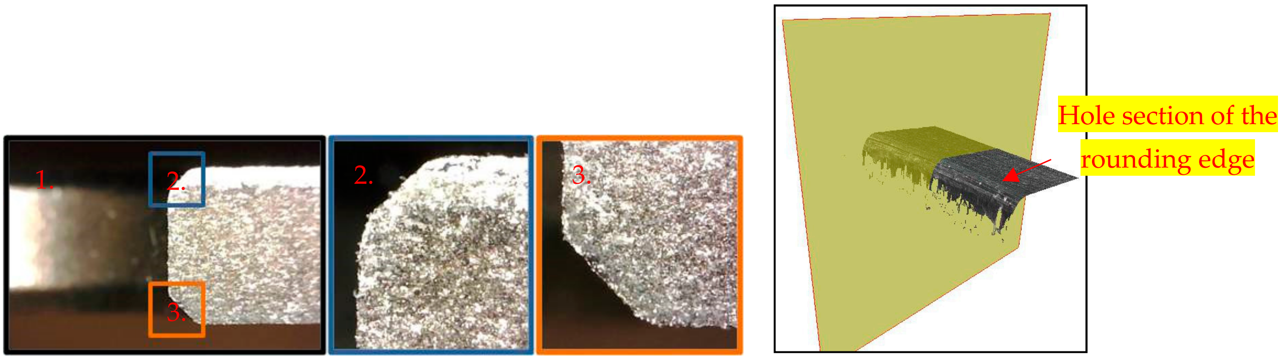


Figure 5. Ra [µm] and Rz [µm] roughness values after drilling and after finishing Inconel718

As a note, results showed that the cutting ability of these brushes is limited, especially when cutting low machinability materials such as Inconel 718. Therefore, great deburring and chamfering of holes became impossible. However, once the hole is chamfered, rounding edges and surface finishing can be done using the flexible abrasive brushes [11]. Figure 6 shows one of the drilled-brushed holes. The process was the next: drilling, chamfering and brushed. The figure 6 and Table 3 shows the rounding edge produced by brushes.



(a) (b)

Figure 6. (a) Hole section and detail of the chamfer and rounding edge. Image 1 (5x), Image 2 (10x), Image 3 (10x). (b) Angle detail measured with optical means of the rounding edge of a hole section (5x).

Table 3. Angle detail – Hole section of the rounding edge.

	Angle/ ⁰	Apex X/mm	Apex Y/mm
Angle 1	102.241	99.452	48.341

For years, edge finishing process has been handmade in many areas, but now the tendency is trying to automate these finishing processes [12]. One automation possibility implies flexible abrasive brushes. But others would be possible, such as using shape tools. In this case, the main drawback is the correct tool positioning and also the tangents to the surface. In addition, it is necessary to consider the fact that many of these holes are placed in curved areas or in difficult access areas to a conventional milling tool. The main problem with the brushes is the lack of repeatability and the rapid wear suffered.

Figure 7 shows some photographs of the brushes following their use. As mentioned above, despite achieving the best results, SC11-400 brush is one of the most expensive, along with the Diamond one. Besides, tool wear on these brushes is greater than the rest. To conclude, regarding the tool wear, BC11 is the most appropriate option on materials such as Inconel 718 Moreover, in some cases is also the best option regarding surface quality achieved.

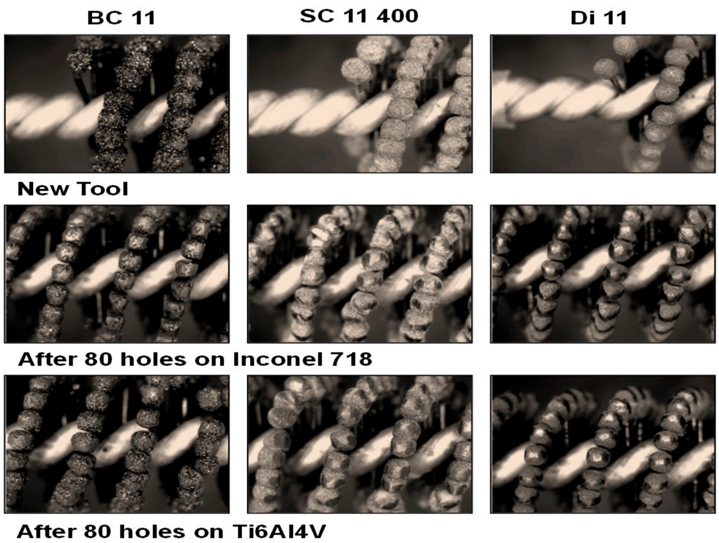


Figure 7. Tool wear on three different brushes. New tool; after Inconel 718; after Ti6Al4V (3x)

5. Automatic process

Polishing and deburring is a process with great automation possibilities, by means of robots [13]. Force feedback control is the key aspect to be considered. Definition of a robotic cell for applying the process is based on accessibility. Flexible brushes are applied on holes for different aeroengine components, cases being produced on Inconel 718, Hastelloy or other nickel alloys are a good task for them. Deburring and edge finishing will be always a step in the process chain. The idea proposed is to work in high-automation mode, in following stages:

- Burr detection, for instance using structured blue light, or other optical means. The location of random implies a random pattern
- Robotic deburring in brush manipulation: a robotic arm can use a spindle with the usual low-torque to give brushed the required rotational speed.
- Final check: optical means will help, in cases of internal hole surface roughness, a roughness meter measurement is obliged.

The proposed system for the automation process consists in a unique superfinished cell capable of working in two different work modes, in particular, with a tool on a robot or with a piece on a robot. In the first of the work modes (MOD1), the idea is to work on pieces of large dimensions (Ø 2400 mm, height 1500 mm, weight 2500 kg) mounted on a rotating table and working with tools mounted on the robot, being this able to access the outer and inner areas of type pieces. The materials to be worked in this case will be heat-resistant alloys with mechanical characteristics equal to or higher than Inconel 718, Titanium 6-4, Jethete type stainless steel or similar. The operations to be carried out will be diverse, highlighting operations of deburring, edge killing and polishing of localized areas and holes, as well as measurement and control operations. In a second mode of work (MOD2), we work with tools mounted in fixed posts, the piece being positioned mounted on the manipulator robot. In this case the pieces to be treated will be units or sets coming from castings or other types of components with maximum dimensions of approximately 1000x1000x1000 mm and maximum weights of up to 120 kg. The materials will have characteristics similar to those indicated for the MOD1 work mode and the operations to be carried out include cutting and sanding processes as well as other operations such as those already mentioned for deburring, polishing and measuring and control. Figure 8 shows the system use to apply the approach.

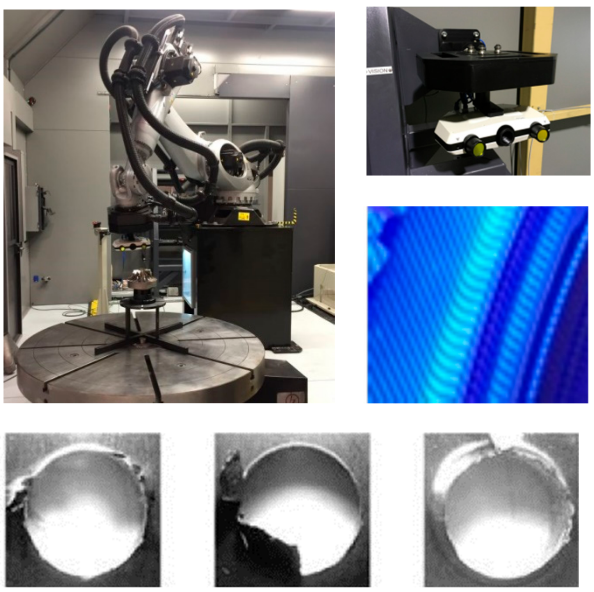


Figure 8. Robotic deburring: robot arm, structured-blue light devices, detail of holes with burrs.

6. Conclusions

Several contributions can be pointed out, namely:

- Preliminary tests on Ti6Al4V show that flexible abrasive brushes are able to reduce the roughness parameters of drilled holes. Furthermore, the final roughness shows less deviation from the average value in comparison to the previous drilling ones. In this material, considering the roughness values, Silicon Carbide 400 grit size brushes are the most suitable.
- Despite the fact that the brushes are not suitable for chamfering or remove large burrs, tests made on Inconel 718 show that these brushes could be a great option for rounding edges and surface finishing. Particularly, BC11 brushes are the most suitable for this operation. After brushing with BC11, the roughness is better, the deviation of results is lower, and their price and wear resistance make them suitable for this aim.
- Brushes are a real choice in industrial environment to have a rapid and efficient way of improving hole inner quality and eliminate burrs at hole edge, both at the entrance and exit of drill bit from plates.
- Polishing, deburring, burr detection or final check by optical means for large pieces, are processes with great automation possibilities by robotic means.

Acknowledgments: The authors gratefully acknowledge the project *Estrategias avanzadas de definición de fresado en piezas rotativas integrales, con aseguramiento de requisito de fiabilidad y productividad IBRELIABLE (DPI2016-74845-R)*, and *Discos de freno premium para trenes de alta velocidad*, by Spanish Ministry of Economy

References

1. Farid, Ali & Sharif, Safian & Namazi, Hamidreza, 2009, "Effect of Machining Parameters and Cutting Edge Geometry on Surface Integrity when Drilling and Hole Making in Inconel 718", SAE International Journal of Materials and Manufacturing. 2. 564-569. 10.4271/2009-01-1412.
2. Tönshoff, H.K., W. Spintig, 1994, "Machining of holes: developments in drilling technology", Annals of CIRP, Vol. 43, pp. 551–561.
3. Turgay Kivak, Kasm Habali, Ulvi Seker, 2011, "The Effect of Cutting Paramaters on The Hole Quality and Tool Wear During The Drilling of Inconel 718.", Gazi University Journal of Science, Turkey.
4. Mannan, M., S. Alsagoff, 2004, "Hole Quality in Drilling of Annealed Inconel 718", Proceedings of the Thirty-Two NAMRC Conference, Charlotte, USA.
5. Rui, L., Hegde, P., Shih, A.J., 2007, "High-throughput drilling of titanium alloys", International Journal of Machine Tools and Manufacture, Vol. 47, pp. 63-74.
6. Shaw, M.C., 1956, Microtechnic 10, pp. 257-265.
7. Astashev, V.K., 1992, Journal of Machinery Manufacture and Reliability, Vol. 5, pp. 65-70.
8. Pujana, J., Rivero, A., Celaya, A., López de Lacalle, L.N., 2009, "Analysis of ultrasonic-assisted drilling of Ti6Al4V", International Journal of Machine Tools & Manufacture, Vol. 49, pp. 500–508.
9. Olvera, D., López de Lacalle, L.N., Urbikain, G., Lamikiz, A, "New strategies for hole making in Ti-6Al-4V", Machining Science and Technology.
10. LNL De Lacalle, A Lamikiz, J Muñoa, MA Salgado, JA Sánchez, "Improving the high-speed finishing of forming tools for advanced high-strength steels (AHSS)", The International Journal of Advanced Manufacturing Technology 29 (1-2), 49-63.
11. D Olvera, LNL de Lacalle, G Urbikain, A Lamikiz, P Rodal, I Zamakona, "Hole making using ball helical milling on titanium alloys", Machining Science and Technology 16 (2), 173-188
12. Á Álvarez, A Calleja, N Ortega, LNL de Lacalle, "Five-Axis Milling of Large Spiral Bevel Gears: Toolpath Definition, Finishing, and Shape Errors", Metals 8 (5), 353
13. S Hameed, HA González Rojas, JI Perat Benavides, A Nápoles Alberro, AJ Sanchez Egea. Influence of the Regime of Electropulsing-Assisted Machining on the Plastic Deformation of the Layer Being Cut. Materials 11 (6), 2018.