Superfinishing robotic cell to automate belt polishing process on critical aeronautical components

M González*, A Rodriguez, O Pereira and L N López de Lacalle

1 Aeronautics Advanced Manufacturing Centre (CFAA), University of the Basque Country (UPV/EHU), Parque Tecnológico de Bizkaia-Ed.202, 48170, Zamudio, Spain.

*Corresponding author: mikel.gonzalez@ehu.eus

Abstract: Surface quality requirements on aeronautical components are critical. When components are manufactured via casting or forging processes, functional surfaces should be machined and, later on, these surfaces should be finished using polishing or other superfinishing techniques. These final processes are usually performed manually by experienced operators, mainly due to their complexity. Nowadays, new technologies provide a chance to automate these processes, but some aspects must be taken into account. On the one hand, it requires technological advances that allow process to be carried out in compliance with the required tolerances. Many of these technologies do not include in their scope the usual materials employed in aeronautical components, which are critical in terms of geometries and machinability. On the other hand, tests must be carried out with different tools and abrasive materials to establish optimum processing conditions in this type of automated process. In this line, the driver of the proposed work is to analyse the behaviour of different abrasive materials and their influence in material removal rate when process parameters increase. Test were performed using a robotic cell equipped with a pneumatic compensation system for pressure and cutting speed control. Obtained results may serve as a basis for defining operating conditions of this type of processes and help to understand their behaviour when dealing with different cutting conditions.

Keywords: Superfinishing, Robotic cell, belt polishing, Aeronautical, Advanced manufacturing.

1. Introduction

In manufacturing industry, requirements for high-precision and high-quality parts with complex geometries are progressively increasing. Turbine blades are one of the most important components in aeronautical engines, and their machining accuracy and surface quality directly determine the performance, operating efficiency and lifetime of power equipment [1]. Surface finishing of machined parts is usually finished by burnishing [2] or polishing [3] operations to reduce surface roughness to the desired level. However, polishing process after CNC milling of these parts usually depends on manual operations. These manual performances are not optimized and their mode of execution is completely operator-dependant, increasing variability due to lack of control methods over process parameters. Automation of finishing process on complex and sculptured surfaces is considered the key to achieve maximum quality, efficiency and to reduce cost.

Industrial robots are positioned as an alternative for development of these processes [4]. There is some background developed in other sectors, as robots are widely used in industry for automation, mainly in assembly tasks or welding processes. Their main advantage is their repeatability and their flexibility, being able to be adapted to all types of processes and parts. In recent years, robotic abrasive
belt polishing (also known as belt grinding) has emerged as an alternative to current manual processes, as a mix of flexibility of manual process and control-precision of CNC machine tools [5]. Belt polishing operations generate high surface quality finishes as well as the removal of excess material, being able to perform large roughing operations, depending on the properties of the abrasive used. In this way, number of previous machining operations can be reduced and, therefore, total manufacturing time. Most of these aircraft components are made from low machinability materials, such as titanium alloys or niquel-based alloys, with thin-walled designs and complex shapes. Inconel 718 represents one of most common materials, due to its excellent mechanical properties at high temperatures, while being a very difficult material for machining. Forces and temperatures in the cutting zone for this material are extremely high due to the high shear stress and low thermal conductivity [6]. On account of this, research that includes Inconel 718 among working materials for robotic belt polishing processes is very scarce. Current studies are focused on force control during process [7-8], which is key to achieving high performance and precision, but tests are not performed in this kind of difficult-to-cut materials. Thus, it is really interesting to develop systems capable of controlling process force, but including Inconel 718 among working materials.

Regarding abrasives employed in these processes, sintered microcrystalline Al2O3 grains are currently the most common material for polishing metals [9]. However, conventional, irregular, polyhedral-shaped grains, instead of machining cleanly, tend to "furrow" metal, collecting heat in the cutting zone. This fact, combining with the low thermal conductivity of Inconel 718, generates high temperatures during process, leading to slower cutting and increased abrasive belt wear. In recent years, new ceramic abrasive technologies were developed for grinding large quantities of material, and one of this material is presented in this work.

The aim of this article is to characterize the material removal capacity of two corundum abrasive belts with different grain profiles (figure 1), a general-purpose belt made with irregular and blocky shape grains and a rough-grinding specific application belt (with precisely shaped, self-sharpening grains designed to slice cleanly), in order to analyse their viability in robotic abrasive belt grinding operations on Inconel 718, using a pneumatic compensation system for control of process pressure.

![Figure 1. (a) General belt for semi-finishing. (b) Roughing belt with precision-shaped grains.](image)

2. Methodology
In order to obtain new information on the behaviour of these abrasives in applications with Inconel 781, a battery of tests was designed by repeating a perpendicular entry-exit movement to the belt, obtaining results of material removal experienced indirectly based on weight difference of the parts.

2.1. Equipment
Tests were carried out on a pneumatically compensated abrasive belt polishing station (figure 2(a)). It is based on two 50 mm wide wheels, one motorised (lower) and another coupled to the pneumatic pressure control system (upper). In this way, it is possible to control polishing pressure, programming...
the robot to perform penetration paths on the upper wheel using a known wheel-retraction distance. The range of admissible compensation pressure is limited to 10 bar, while the maximum rotation speed is 2,500 rpm.

![Polishing station with pneumatic compensation. (a) Virtual environment recreation in Robotmaster.](image)

**Figure 2.** (a) Polishing station with pneumatic compensation. (b) Virtual environment recreation in Robotmaster.

The robot used for tests is the 6-axis KRC4 KR240 R2500 "Prime Absolute Accuracy" model from KUKA, controlled by KRC4 system. For workpiece gripping, it includes a gripper-head with a pneumatic drive and a clamping system of 2 interchangeable fingers, able to grip workpieces up to 1050x1050x1050 mm and 125 kg.

2.2. Virtual environment
For path planning, the entire robotic cell environment is recreated to enable control of robot's movements. The design of components and path planning was carried out in MASTERCAM, while the simulation for collision-control and optimisation of robot's movement configurations was performed through the ROBOTMASTER extension. The definition of this virtual environment is the key for the success of automation process, but set-up and details are out of the scope of this work.

2.3. Design of experiments
As previously mentioned, the aim of these tests is to characterize the material removal capacity of two abrasives, analysing their wear and behaviour under different cutting conditions. For this purpose, 3 tests were carried out for each abrasive, distributed as follows:

- **Base** test: Baseline conditions of low pressure and cutting speed.
- **Pressure** test: Two-fold increase in polishing pressure compared to the base test.
- **Cutting** speed test: Two-fold increase in cutting speed compared to the base test.

For each test, results are obtained for material removal rate (measured in mm3/s), obtained indirectly by weight difference of the pieces after each operation, keeping the cutting section constant throughout the process. Measurements are made using a precision electronic balance CI-3200 CBC with a resolution of 0.1 g.

2.3.1. Control settings. The application of robotic cell in polishing process allows for identification and control of the parameters involved in the process, being able to set those that are useful when comparing the effects of the variation of rest of parameters. For each test, 4 cycles of 23 seconds in total were carried out, divided into 3 operations of 5, 8 and 10 seconds. Thus, the behaviour of sanding belts was analysed for operations with different workloads, showing their evolution throughout successive cycles in order to study wear effect.
The offset retraction distance was set at 10 mm at the start of each operation, which is enough to enable removal of material at the established operating times and process conditions. Pneumatic drive is in charge of keeping polishing pressure constant throughout each operation.

Material used for testing consists of 2 equal test pieces of Inconel 718 aged (42-50 HRC) of 35 mm width, 10 mm height and 200 mm length, one used for each abrasive. Abrasive corundum belts were selected according to their application. Irregular P40 sized conventional grain belt was selected as baseline for general purpose (figure 1(a)). A specifically designed belt made with precision-shaped triangular grains of size P36+ was chosen as second alternative for large roughing with heat resistant materials (figure 1(b)).

2.3.2. Variables. After establishing the offset retraction and time distribution, it was of special interest to check the effect of varying the rest of characteristic parameters of the process in order to analyse the behaviour of abrasives. These parameters to be studied were pressure and cutting speed, decisive when it comes to increasing productivity, but also closely linked to the development of high temperatures, highly critical in this type of abrasive processes.

Three tests were organised for each abrasive, as mentioned above. Firstly, a test was carried out under low conditions of pressure and cutting speed, as a baseline for rest of comparative tests, setting the compensation pressure at 1 bar and monitoring the rotational speed for a cutting speed of 15 m/s.

The rest of tests were carried out by increasing initial values of pressure or cutting speed by 100%. In this way, the aim was to analyse the variation in material removal rate and thermal impact produced on the parts, checking which strategy appears to be the most suitable for each type of abrasive.

3. Results

Table 1 shows the numerical value of process parameters used in each test. The results obtained for the material removal rate (in mm³/s) are shown in table 2, graphically represented in figure 3 in order to show the behaviour of both abrasives under different cutting conditions.

| Cycle | Process time | Total time | Base test a | Pressure test b | Cutting speed test a | Base test b | Pressure test b | Cutting speed test b |
|-------|--------------|------------|-------------|----------------|---------------------|-------------|----------------|---------------------|
| 1     | 8            | 13         | 19.16       | 59.70          | 67.09               | 54.92       | 191.73         | 232.06              |
|       | 10           | 23         | 13.14       | 46.65          | 57.18               | 48.33       | 184.76         | 225.43              |
| 2     | 8            | 36         | 10.95       | 36.10          | 39.38               | 50.80       | 171.40         | 200.75              |
|       | 10           | 46         | 8.76        | 37.77          | 51.34               | 43.94       | 167.33         | 215.11              |
| 3     | 8            | 59         | 8.21        | 29.99          | 37.34               | 39.54       | 160.36         | 197.43              |
|       | 10           | 69         | 6.57        | 26.66          | 24.50               | 37.35       | 154.55         | 160.60              |
| 4     | 8            | 74         | 6.57        | 26.66          | 21.00               | 28.56       | 139.44         | 200.38              |
| 10    | 8            | 82         | 6.84        | 26.38          | 24.80               | 28.83       | 140.89         | 213.64              |
|       | 10           | 92         | 7.67        | 26.66          | 23.34               | 31.85       | 138.28         | 195.96              |

a General belt
b Roughing belt
4. Analysis of the results

Results show a significant increase in material removal rate when increasing process parameters. With a 100% increase in pressure, improvements of 241% and 286% are experienced for general purpose material belt and roughing belt respectively. When only cutting speed is increased by the same 100% improvement rises to 273% and 385% respectively. Similar gains are achieved for the case of general-purpose belt, while for roughing belt the increase in cutting speed generate higher material removal rates.

![Figure 3. Representation of material removal rate (mm³/s) obtained in tests.](image)

![Figure 4. Comparison of material removal over the course of trials.](image)

In general, precision-shaped grain belt achieves much higher material removal rates, between 3-4 times higher, in line with its specific application for large roughing. Figure 5 shows how this abrasive material experiences less variation, keeping very similar values for the test in which cutting speed is increased. However, in the case of general-purpose belt, the increase in process conditions barely manages to balance out the effects of wear, which are much more pronounced for this case.
It is proven how high values of pressure and cutting speed contribute to increase productivity in a similar way. However, these parameters have a direct impact on process temperature in different ways. During test with increased cutting speed, thermal impact slightly rises without producing significant burns in the cutting zone. In contrast, when pressure is increased, general-purpose belt generates significant burns in the cutting section (figure 6(a)), being the depth of thermal impact on workpiece higher. Precision-shaped grain belt provides a better finish in terms of thermal impact, without burns in the rough section of the part (figure 6(b)). Thus, if productivity needs to be improved by increasing material removal rate, the best strategy would be to increase cutting speed to obtain maximum removal rates while minimizing thermal impact on workpiece.

Finally, surface finish is analysed at the end of each work cycle by a roughness tester, on both types of abrasives under different cutting conditions (figure 7). Obtained results for general-purpose irregular grains are shown to be lower, in order of 50% compared to precision-shaped triangular grains, whose use is more oriented to roughing tasks regardless of surface requirements. Variations in process parameters hardly have any influence on obtained results. For both abrasive types, the highest material removal rate occurs in the first cycle. This value that tends to decrease throughout tests due to wear and loss of sharpness in abrasive grains. This phenomenon is a bit smaller in the case of precision-shaped roughing belt with losses of 15% at the end of tests on average, being up to -40% for the other case.

Conventional general-purpose grain loses its sharpening properties earlier and, as a consequence, abrasive marks on workpiece are reduced, increasing friction and thus the heat generated, as shown before. Figure 8 presents results obtained by confocal microscopy showing the loss of abrasive material on the belts (compared to figure 1) due to wear caused by pressure test.
5. Conclusions

Results show that the automation for polishing process using abrasive belt with pneumatic compensation systems for pressure control is a feasible alternative to reduce human-dependant manual processes. In this line, some detailed conclusions are obtained in this work:

- The correct choice of abrasive material is key to achieving the objectives of the polishing process. Results show that, when large material volume should be removed, precision-shaped abrasive belts are the most suitable alternative. Sharp shape eases cutting and reduces surface in contact with workpiece, decreasing friction and achieving a more effective removal.
- Higher values of pressure and cutting speed contribute to increase productivity in a similar way (i.e.: improvements of 241% and 286% when doubling them respectively).
- Belt life (tool wear) is directly related with process parameters. Increasing pressure and cutting speed, tool life decrease, but gentler slopes are shown using precision-shaped belt (figure 5).
Polishing pressure should be taken into account regarding surface burning (lower values are recommended to avoid these kinds of damage). If material removal should be maximised, it is proven that the best strategy is to increase cutting speed, obtaining higher values of material removal while minimising the effect of burns on final part.

Surface roughness is clearly process-tool dependant. Using different abrasive materials and grain, different surface roughness values can be obtained. The best ratio between removal rate and finishing should be defined for each use-case.

5.1. Future lines
Work developed provides a new comparative framework for abrasive belts in Inconel 718 applications. The provided data set can be used as a baseline for setting operating conditions for this type of products and can be extended by adding different types of abrasives with different grain size and shape configurations.

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