Blisk blades manufacturing technologies analysis

A. Calleja[a]*, H. González[b], R. Polvorosa[c], G. Gómez[b], I. Ayesta[c], M. Barton[d], L.N. López de Lacalle[c]

[a]Department of Mechanical Engineering, University of the Basque Country (UPV/EHU), Nieves Cano 12, Vitoria 01006, Spain
[b]Department of Mechanical Engineering, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, Bilbao 48013, Spain
[c]CFAA—University of the Basque Country (UPV/EHU), Parque Tecnológico de Zamudio 202, Bilbao 48170, Spain
[d]BCAM–Basque Center for Applied Mathematics, Alameda de Mazarredo 14, Bilbao48009, Spain

Abstract

The paper presents blisk blades manufactured by different manufacturing processes. In this sense, different milling trajectories are presented, and, super abrasive machining strategies and EDM technologies are also tested. Machining times, costs and surface finish are analysed in order to determine optimal machining process for blisk manufactured in low machinability materials.

Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2019.

Keywords: Blisk; Low machinabilty; Machining; SAM; EDM

1. Introduction

Aeronautic sector predicts that air traffic will continue a growing tendency, and, therefore, airplanes manufacturing companies will need to meet required necessities. Aeronautic industry should satisfy this demand according to a series of aspects regulated by European regulations such as efficiency, noise, and fuel consumption. Consequently, airplane components manufacturing processes should be optimized. A special attention should be paid to motor components which are the most expensive parts of the airplanes.. Design and manufacturing processes for blisks (blade integrated disks) present alternatives to conventional fir - tree concept. Integrated design presents advantaged related to aerodynamic flux and higher efficiency in terms of fuel consumption [1]. However, integral disc manufacturing requires blisks to be made of hard to machine alloys (Ti-6Al-4V and Inconel 718) which represents a machining technological challenge from the economic and technological point of view [2].

Selected machining process for component manufacturing will depend on the component material [3] and geometry [4]. In this sense, several studies have focused on blisk milling processes, in which the finishing operation is the one with most influence on component final quality [5]. Nevertheless, previous operations such as roughing ones do also require special attention due to their relation with process productivity. Morishige and Takeuchi [6] studied 5-axis roughing operations optimization. Some CAD-CAM software limitations have motivated researchers towards special modules or software development for a better control of complex surface machining trajectories. 5-axis roughing and finishing operations are applied to "centrifugal compressor impellers" and studied in [7] an application developed for the programming of machining trajectories for these type of components. The use of different programming languages [8] for trajectories optimization algorithms is an appropriate alternative for the avoidance of commercial software limitations and flexibility improvement. In this line, the use of approximation algorithms for the specific case of impeller ruled surfaces with cylindrical tools [9] improves the efficiency of the process. Impeller trajectories programing, whose geometry is obtained by inverse engineering, is studied in [10], using a module in CBIMS created for machining process planning [11]. Although there are many machining trajectories applicable to blisks and impellers, they can be mainly classified into (i) point milling and (ii) flank milling. Point milling trajectories are based on the use of the tool tip whereas in flank milling trajectories the tool flank is compromised in the cut of material, which considerably improves the operation productivity. However, it is not always possible to include flank milling trajectories. On the other hand, the main disadvantage of flank milling trajectories is related to process stability that can be affected by several vibrations if cutting parameters are not correctly selected. Flank milling trajectories guarantee tangential contact between the ball-tapered cylindrical tool surface and the different generatrixes that define the surface. This way, it is possible to machine with an axial depth equal to the tool flank. This strategy allows to machine large quantities of material, which is directly beneficial for the productivity of the process. However, to maintain this efficiency of the process it is necessary to resort to a tool of large dimensions that would reduce the risk of tool bending and the appearance of vibrations inherent to this type of machining operations. Numerous works have been developed in the field of the optimization of flank milling machining strategies using the surface of the tool [12] and optimal positioning procedures for flank milling of surface machining with cylindrical tools [13]. In the case of ruled developable surfaces, the tool flank is kept tangent to the surface. In the case of non-developable ruled surfaces, the situation is a lot more complicated because the tangent plane changes along a ruling. This is why it is not possible to adjust the tool flank to the surface [14].

Moreover, there are also studies for milling strategies based on algorithm development for minimum machining error. [15] focuses on the approximation quality between the design surface and the milled conical envelope considering pre-defined conical milling tools. Traditionally, the initial trajectory of the milling axis is assumed as an input and users' intervention is necessary to provide a meaningful initial trajectory. Here, a recent research on automatic detection of conical envelopes [16] is adopted, showing that this initialization strategy, when incorporated to real manufacturable process, reduces the milling time significantly by detecting large envelopes within fine machining tolerances.

On the other hand, regarding innovative technologies for blisk manufacturing, super abrasive machining (SAM) was presented in [17] as a solution to increase machining productivity during the production of blade and turbine disks. SAM technology outstands for combining grinding technology at milling rates. Moreover, in comparison to other grinding technologies such as creep fatigue grinding, it improves machining feeds [18], material removal rates and dimensional quality [19]. All these characteristics make SAM a reliable alternative for nickel-based super alloy IBRs manufacturing [20, 21].

SEDM studies do also outstand among very hard materials (> HRC) and closed blisk geometries. Due to the high process times of EDM, it is usually limited to blisk with very complex cavities. Most of the authors researching on blisk manufacturing by SEDM, are focused on path calculation and electrode design, since commercial software lacks modules for these tasks [22, 23]. Some have ventured to erode the pieces to see the problems that may appear during their manufacturing, but there are few works that compare SEDM with other blisk manufacturing processes.

Concluding, blisk manufacturing is being studied independently, from point of view of various technologies, and, process comparison will determine optimal manufacturing parameters depending on component characteristics. In this work, blisk blades are manufactured by different manufacturing processes. In this sense, milling strategies based on different tool path determinations are compared to super abrasive machining strategies and EDM technology. Machining times, costs, and surface finish are analysed in order to determine optimal machining process for Inconel® 718 blisk blades manufacturing. Followed methodology includes different stages. First of all, blisk CAD geometry is defined. Afterwards feasible machining processes are selected for blades manufacturing. Machining strategies, tools geometry and machining parameters are programmed in each case. Afterwards, blades are machined according to programmed strategies. Finally, each process characteristics such as machining times, costs, and surface finish are analysed.

2. Test design and methodology

For tests design, blisk type geometries are chosen in order to be manufactured using four different manufacturing processes. In section 2.1. milling technology is applied and CAM software is used for milling trajectories programing. In section 2.2. milling technology is applied, but, in this case, specific algorithm is developed for machining strategy. In section 2.3. SAM technology is performed. Finally, in section 2.4. SEDM technology is described.

In the following subsections, process equipment, parameters, and results are shown for each technology. The same process parameters (feed (F), spindle speed (S), axial depth (ap), and radial depth (ae)) are analised in every case. Tool characteristics such as material and geometry is also described. Besides, performed machining strategy is explained.

2.1. Milling

Selected geometry for milling technology validation is a Ti6Al4V blisk with 18 blades around a 200mm diameter (Fig1a and Fig1b). The tests were carried out in a five-axis high speed machining center Ibarmia ZV25/U600 Extreme. Regarding milling operations (Table 1), roughing, semi-finishing, and blade and hub finishing operations are programed with NX12 from Siemens. Flat tool geometry is used for roughing strategies whereas tapered ball nose end mills and ball nose end mills are used for semi-finishing and finishing operations respectively. In relation to milling strategies, zig-zag with lifts is performed for roughing and hub finishing, and, helicoidal strategies are programed for semi-finishing and blade finishing.

Table 1. Milling process parameters definition.

Operations	Tool	Process parameters (F,S, ap, ae)	Strategy
Roughing	Flat end ø10 R2.5	630 mm/min, 3000 rpm, 75% tool ø, 20% tool ø	Zigzag with lifts
Semi-finishing	Tapered ball nose end ø6 α4°	750 mm/min, 4000 rpm, 5mm, 1-2 mm	Helicoidal
Blade finishing	Ball nose end ø6	400 mm/min, 4000 rpm, 0.6 mm, 0.5 mm	Helicoidal
Hub finishing	Ball nose end ø6	475 mm/min, 6000 rpm, 0.6 mm, 10% tool ø	Zigzag with lifts

Process time, cost and surface finish values are detailed in Table 2. In this case, blade semi-finishing is the operation that lasts longer with approximately 3h followed by roughing with 1h. Semi-finishing and hub finishing operations last around 30min each of them. On the other hand, for milling cost determination, machine €/h cost, tool cost, material cost and cutting fluid cost is taken into account. Due to confidentiality reasons the price is not being broke down.

Finally, surface finish is measured for finished component (roughing and semi-finishing surface finish values are not obtained). ATOS 5M GOM scanning system is used for surface quality measurement. This equipment is based on the triangulation effect with two cameras. In this case surface finish values are 11 µm for blade finishing and 17 µm for hub finishing.

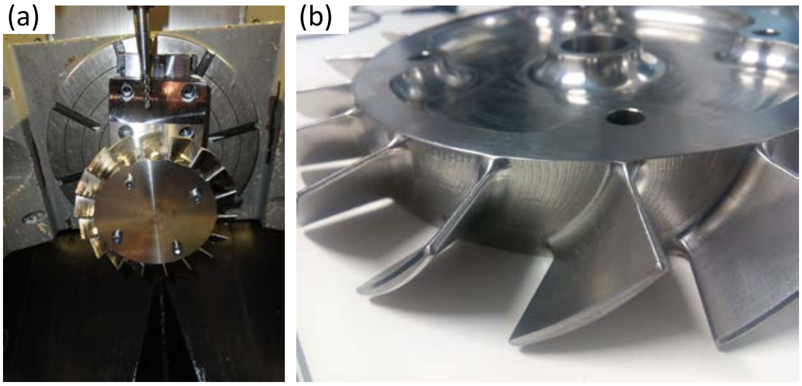

Fig. 1. (a) blisk semi-finish process; (b) finished blisk component.

Table 1. Milling process analysis.

Operations	Time	Cost	Surface finish
Roughing	1h 3min 18s	750 €	-

Semi-finishing	25min 12s	700 €	-
Blade finishing	3h 3min	830 €	11 µm Ra
Hub finishing	37min 30s	713 €	17 µm Ra

2.2. Algorithm based milling

Due to programming limitations generally associated to CAM software, and, in order to be able to obtain an optimized milling strategy for finishing operation, algorithm based strategy is develop in this section.

Table 3. Algorithm based milling process parameters definition

Operations	Tool	Process parameters (F,S, ap, ae)	Strategy
Finishing	Tapered ball nose end ø1.5 α3°	500 mm/min, 6000 rpm, 24mm (tool length), 0.2 mm	Flank milling (algorithm)

The algorithm is based on the approximation between the designed surface and the tool conical envelope. Automatic detection of conical envelopes [16] is adopted, showing that this initialization strategy, when incorporated to real manufacturable process, reduces the milling time significantly by detecting large envelopes within fine machining tolerances. Mathematical calculation based on the tangential movability of a truncated cone along a free-form surface and is used in the algorithm that computes conical envelopes that fit the input reference geometry.

Milling simulations are conducted in a five-axis KONDIA HS1000 machining center, being numerically controlled by Heidenhain iTNC530. Manufactured geometry are Ti6Al4V blisk blades samples (Figure 2b). In this case, roughing and semi-finishing operations do not present research interest, being the blade finishing strategy the studied operation (Table 3).

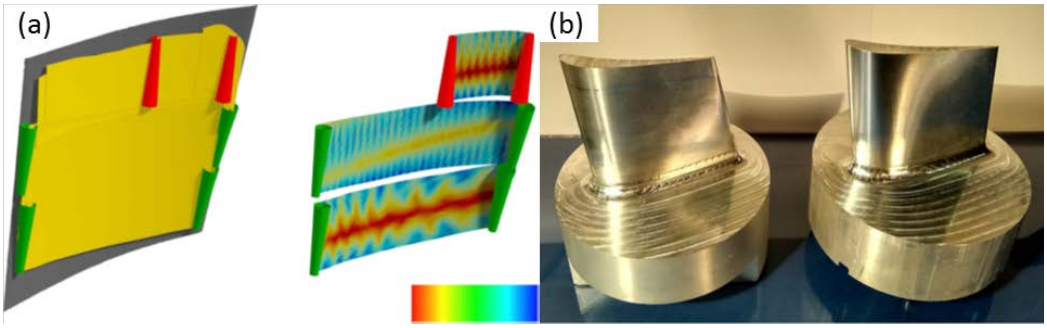

Fig. 2. (a) tool axis motion and color-coded approximation; (b) manufactured blisk blades

Table 4 shows algorithm based finishing operation time, cost and surface finish values. Finished components are measured with ATOS 5M GOM scanning system. In this case, flank milling operation only consumes a few minutes being a very productive operation. Therefore, machining tie is reduced being reduced the price of the machine use (€/h). Moreover, developed algorithm provides excellent surface finish results.

Table 4. Algorithm based milling process analysis.

Operations	Time	Cost	Surface finish
Finishing	2min	640€	6 µm Ra

2.3. Super Abrasive machining

SAM technique is applied to Inconel 718 blisk blades (Figure 3). Experimental tests are carried out in a five-axis high speed machining center Ibarmia ZV25/U600 Extreme (Spindle rotation up to 18000 rpm). SAM process parameters are defined in Table 5. Selected tool is a diamond & CBN electroplated tool of 20mm diameter. Roughing operation is performed following a slotting strategy and flank milling strategy is selected for finishing strategy.

Table 5. SAM process parameters definition.

Operations	Tool	Process parameters (F,S, ap, ae)	Strategy
Roughing	Diamond & CBN Electroplated tool ø20mm	450mm/min, 14000 rpm, 20mm, 0.2 mm	Slotting
Finishing	Diamond & CBN Electroplated tool ø20mm	500mm/min, 14000 rpm, 20mm, 0.2 mm	Flank milling

Finished components are measured with ATOS 5M GOM scanning system. Roughing surface finish results are not measured. In this case, both operations only consume a few seconds.

Table 6. SAM process analysis.

Operations	Time	Cost	Surface finish
Roughing	1min 43s	740	-
Finishing	14s	690	7 μm Ra

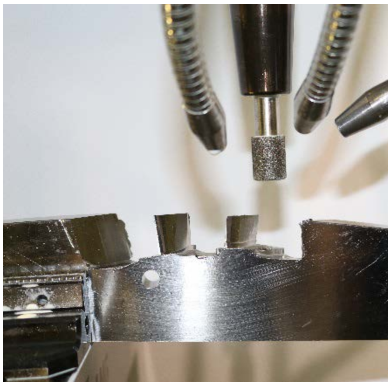

Fig. 3. (a) SAM blisk blades.

2.4. SEDM

For the SEDM process, a shrouded blisk with an outside diameter of 300mm and 35 blades/cavities was chosen (see images 4a and 4b). Although normally aeronautical materials (for example, nickel base alloys) are used for this type of pieces, for this disc AISI 403L stainless steel was used. Since for the SEDM process the behavior of both materials is similar and getting more steel simple.

Both electrode design and the erosion trajectories were obtained using the methodology proposed in Ayesta et al. [22]. Two axis, linear axis Z and the rotary axis C (around Z), were interpolated during trajectory. In addition, an additional rotary axis (axis B) has been used for positioning. Figure 4c shows an image of the previous tests carried out before the erosion of the disk. In this test, a blade wear cut in order to measure it and its shape can be seen. Due to the shape of the cavity, erosion was carried out in two clamping positions. First the erosion of half of the cavity (in height) of one side of the disk (upper cavity) was made, the disk was rotated and the other half (lower cavity) was finished until the channel between blades was opened.

Table 7. SEDM process parameters definition.

	Tool (geometry and material)	Process parameters (I,V,t_i,t_0,S)	Strategy
Roughing	Upper and lower. POCO 200	14A, 160V, 200µs, 25 µs, 35V	[22]. Z linear axis and C rotary axis interpolation
Finishing	Upper and lower. POCO 200	4A, 200V, 25µs, 15µs, 60V	

The geometry of the disc allows the use of multiple electrodes to erode several cavities at the same time. Thus, more energetic parameters can be used and save time. Even a single electrode could have been used to erode all the cavities at once, but in this case triple electrodes were chosen due to the manufacturing of a single electrode was complex. Four different types of electrode were used, two for roughing and two for finishing, one of each type for each side of the disc. All the electrodes were triples and the material used was graphite POCO 200. Table 7 shows SEDM process parameters.

The erosion was carried out in an ONA NX5 machine, first roughing and then finishing. Table 8 shows process parameters. The whole erosion of the disk lasted around 170h, of which 98 h correspond to roughing.

Table 8. SEDM process analysis.

Operations	Time	Cost	Surface finish
Roughing	98 h	2450 €	8 µm Ra
Finishing	72 h	1800 €	2.2 µm Ra

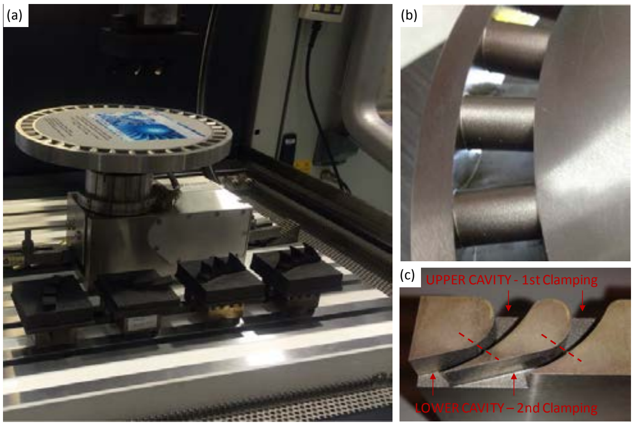

Fig. 4. (a) The whole blisk and the electrodes; (b) cavity image; (c) a previous test in which a cut was made to measure.

3. Results and conclusions

After the machining of blisk blades geometries in different difficult to cut materials (titanium alloys, nickel alloys and steel alloys) using milling, algorithm based milling, SAM and SEDM technologies, measured process values are analysed. In this case, in the four cases, machining times, cost and surface finish values are measured.

Regarding machining times, algorithm based technologies and SAM technologies are faster than milling technologies. Moreover, SEDM is the one with longer machining times due to process performance.

On the other hand, in relation to surface finish, SEDM is the one that provides better surface finish values. However, very good results are also obtained with SAM and algorithm based milling technologies, both under 10 µm.

Finally, cost estimation, although approximated shows the difference between machining times. For longer machining process, machine cost increments. Tool cost expensive in SEDM, being necessary to manufacture the electrodes. Besides SAM tools are also more expensive that standard milling tools.

Acknowledgements

The authors wish to acknowledge the financial support received from HAZITEK program, from the Department of Economic Development and Infrastructures of the Basque Government and from FEDER founds, related to the projects with acronym HARDCRAFT and TURALOY. Besides, thanks are also addressed to the Vice chancellor of innovation, social compromise and cultural action from UPV/EHU (Bizialab program from Basque Government) and to Spanish Project MINECO RTC-2017-6039-5.

References

[1] Klocke, F., Klink, A., Veselovac, D., Aspinwall, D.K., Soo, S.L., Schmidt, M., Schilp, J., Levy, G., Kruth, J., 2014. Turbomachinery component manufacture by application of electrochemical, electro-physical and phot onic processes, Cirp Annals-Manufacturing Technology 63, p. 703-726.
[2] Klocke, F., Zeis, M., Klink, A., Veselovac, D., 2012. Technological and Economical Comparison of Rough ing Strategies via Milling, EDM and ECM for Titanium- and Nickel-based Blisks, 1st Cirp Global Web Confer ence: Interdisciplinary Research in Production Engineering (Cirpe2012) 2, p. 98-101.
[3] M. Bussmann, E. Bayer, 2009. Blisk Production of the Future. Technological and logistical aspects of futur e-oriented construction and manufacturing processes of integrally bladed rotors, 19th International Symposium on Airbreathing Engines 1, p. 568-577.
[4] Klocke, F., Schmitt, R., Zeis, M., Heidemanns, L., Kerkhoff, J., Heinen, D., Klink, A., 2015. Technological and Economical Assessment of Alternative Process Chains for Blisk Manufacture, Mic2015 -15th Machining I nnovations Conference for Aerospace Industry 35, p. 67-72.
[5] Calleja, A., Fernandez, A., Campa, F.J., Lamikiz, A., Lopez de Lacalle, L. N., 2013. Reliable Manufacturin g Process in Turbine Blisks and Compressors, Manufacturing Engineering Society International Conference, (Mesic 2013) 63, p. 60-66.
[6] Morishige, K., Takeuchi, Y., 1997. 5-Axis Control Rough Cutting of an Impeller with Efficiency and Accu racy, 1997 Ieee International Conference on Robotics and Automation - Proceedings, Vols 1-4, p. 1241-1246.
[7] Young, H.T., Chuang, L.C., Gerschwiler, K., Kamps, S., 2004. A five-axis rough machining approach for a centrifugal impeller, International Journal of Advanced Manufacturing Technology 23, p. 233-239.
[8] Bohez, E.L.J., Senadhera, S.D.R., Pole, K., Duflou, J.R., Tar, T., 1997. A geometric modeling and five-axis machining algorithm for centrifugal impellers, Journal of Manufacturing Systems 16, p. 422-436.
[9] Liang Quan, Wang Yongzhang, Fu Hongya, Han Zhenyu, 2008. Cutting Path Planning for Ruled Surface I mpellers, Chinese Journal of Aeronautics 21, p. 462-471.
[10] Chen, S.L., Wang, W.T., 2001. Computer aided manufacturing technologies for centrifugal compressor i mpellers, Journal of Materials Processing Technology 115, p. 284-293.
[11] Cho, M., Kim, D., Lee, C., Heo, E., Ha, J., Chen, F.F., 2009. CBIMS: Case-based impeller machining stra tegy support system, Robotics and Computer-Integrated Manufacturing 25, p. 980-988.
[12] Gong, H., Cao, L.X., Liu, H., 2005. Improved positioning of cylindrical cutter for flank milling ruled surf aces, Computer-Aided Design 37, p. 1205-1213.
[13] Gong, H., Wang, N., 2009. Optimize tool paths of flank milling with generic cutters based on approximati on using the tool envelope surface, Computer-Aided Design 41, p. 981-989.
[14] Senatore, J., Landon, Y., Rubio, W., 2008. Analytical estimation of error in flank milling of ruled surfaces , Computer-Aided Design 40, p. 595-603.
[15] Calleja, A., Bo, P., Gonzalez, H., Barton, M., Norberto Lopez de Lacalle, Luis, 2018. Highly accurate 5-a xis flank CNC machining with conical tools, International Journal of Advanced Manufacturing Technology 97, p. 1605-1615.
[16] Bo, P., Barton, M., Pottmann, H., 2017. Automatic fitting of conical envelopes to free-form surfaces for fl ank CNC machining, Computer-Aided Design 91, p. 84-94.
[17] Włodzimierz Wilk, Jacek Tota, 2007. Modern technology of the turbine blades removal machining, Proce edings of the 8 International Conference Advanced Manufacturing Operations, p. 355.
[18] Guo, C., Ranganath, S., McIntosh, D., Elfizy, A., 2008. Virtual high performance grinding with CBN whe els, CIRP Annals 57, p. 325-328.

[19] Petrilli, R., 2012. Super abrasive machining for PM, Metal Powder Report 67, p. 38-41.
[20] Erickson, R.E., 2011. Method of Machining between Contoured Surfaces with Cup Shaped Tool.
[21] Erickson, R.E., Faughnan, P.R., 2011. Method of Machining Integral Bladed Rotors for a Gas Turbine Engine.
[22] Ayesta, I., Izquierdo, B., Sanchez, J.A., Ramos, J.M., Plaza, S., Pombo, I., Ortega, N., 2016. Optimum electrode path generation for EDM manufacturing of aerospace components, Robotics and Computer-Integrated Manufacturing 37, p. 273-281.
[23] Kang, X., Liang, W., Yang, Y., Zhao, W., 2018. Maximum free distance method for electrode feeding path planning in EDM machining of integral shrouded blisks, Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology 51, p. 514-520.