ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP061

STATE OF THE ART OF NIOBIUM MACHINING FOR SRF APPLICATIONS

P. Naisson†, S. Atieh, K. Scibor, P. Trubacova, CERN, Geneva, Switzerland
F. Dumont, D. Fabre, F. Valiorgue, ENISE, LTDS, Saint-Etienne, France

In the frame of the HL-LHC project, high purity niobium machining has to be mastered to achieve high shape accuracy and surface quality requested. Niobium machining could start from bulks or previously formed sheets. CERN developed both practical and advanced specific knowledge about niobium processing. Especially, the on-going fabrication requires high-quality cutting tools, state of the art machines, both in term of precision and stability, efficient programming solutions, and adequate lubrication mode.

The present paper will be based on the manufacturing of CRAB cavities, with a focus on the machining issues (3D shapes, surface roughness). Then, we will introduce the approach used at CERN: first, the ability of the studied parameters to allow efficient machining, secondly the qualification and understanding of the technologies. We would take as an example the cutting fluid selection. After comparing three cutting fluid, we will introduce elementary friction tests carried out to identify the frictional behaviour and its impact over the resulting surface, in terms of surface quality (roughness, shape) and characteristics (thermal history of the finished surface). Finally, we will discuss the on-going research for advance niobium machining, including cryogenic machining, and the opportunities given by modern machining strategies.

NIOBIUM MACHINING AND DEMANDS

Machining of niobium is known since the 1950s especially in nuclear and physics applications. At the time, it has been found that this pure material behaves like soft annealed copper, by its tendency to gall and form long chips. Constant flood cooling, sharp cutting edge and low cutting speed were then the adequate solution for producing parts. Its application in SRF cavities fabrication increased. Parts that are more complex had to be machined and assembled. Electron beam welding is the only joining technology able to produce clean and structured connections but requires precise alignment and surface preparation in order to ensure high-quality parts. Also, SRF parts shape goes from elliptical [1] to quasi asymmetrical [2, 3] (Fig. 1) and thus implies sheet metal forming as the first process. Machining is then the key process to transform a near net shape to the electron-beam welding requirement, in terms of ~~connection shape~~ joint configuration and accuracy.

† pierre.naisson@cern.ch

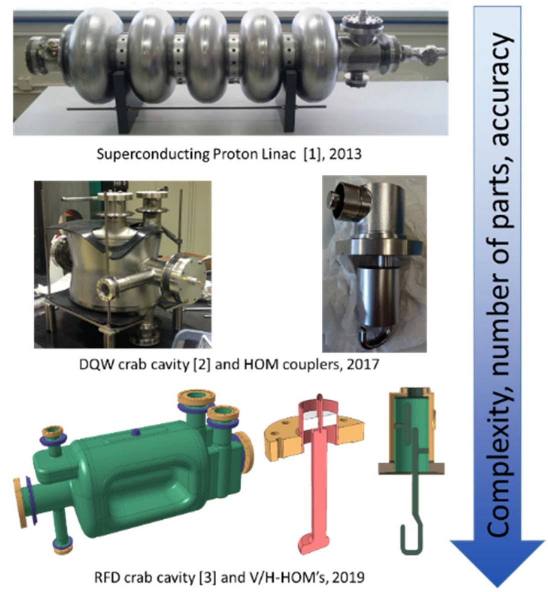

Figure 1: Evolution of SRF cavities produced at CERN, increasing in quality and complexity.

Machining wise, niobium is difficult because of its refractory behaviour, abrasive, low yield stress, and high density. This leads to a difficult adiabatic shearing process, which is the base of the high-speed machining technologies. Moreover, parts are even more complex, from their intrinsic shape (not circular nor prismatic) and quality requirements, such as surface roughness and shape accuracy.

This lead CERN main workshop to investigate niobium machining, on one hand, to be able to process current and future demands, and on the other hand to better understand material, tool, coolant and machine behaviour.

ENVIRONMENT MASTERING

The first step of machining optimisation relies on a stable environment. In this particular case, the machine tool has to be sufficiently stiff to avoid bending and vibration during the machining process and has to be precise enough to achieve requested shape accuracies. CERN main workshop is thus equipped with state of the art of machine tool, with regular geometrical accuracy controls. The complex shape also requires an efficient CAD/CAM (computer-assisted design/manufacture) workflow. By working directly on the 3D model, hence the exactly designed surface and programming smooth toolpath, the geometrical accuracy and the surface quality can be achieved.

Most of the cavity subcomponents are obtained at CERN through sheet metal processing, such as deep drawing,

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP061

electrohydrofoming [4], bending and stamping. These processes result in highly stressed parts, with a large variation of shape in the extra length left for the forming process (Fig. 2). This extra length has to be trimmed and prepared for electron beam welding, without a scratch or damage the RF surface.

Figure 2: DQW crab cavity subcomponent before first machining, after the deep drawing process. See wrinkles on the top side.

Therefore, CERN tackles these issues with specific clamping systems, with metrology alignment of the part mounted on the fixture, and stress limitation during tightening of the component onto the fixture. The key step in this approach is the transfer of the metrology measurements into actual machining referencing (Fig.3), and an adaptation of the toolpath to the exact material to be removed. A four stages approach is used: the part is measured in a Coordinate Measuring Machine (CMM) at its free stress state. Then the part is mounted and clamped in the fixturing jigs. A new CMM control is realised, ~~plus~~ including some reference points of the fixturing device. Finally, geometrical transformation is applied in order to compensate misalignment of the part on the fixture directly on the machining machine controller.

Figure 3: DQW crab cavity subcomponent during machining, with an optimized clamping system.

Because of the increasing complexity of parts (deeper machining, long overhang tools, surface quality), CERN aims to integrate also machine volumetric error compensation, which would allow reaching a global accuracy with the 10 micrometres range on the whole part volume. In addition, new tools development and machining strategy are evaluated for SRF applications.

PROCESS OPTIMISATION

As mentioned previously, the state of the art relies on high-speed steel tools and constant flood coolant. With modern machining strategy, carbide tool and optimized coolant could be assessed through machinability aspect and surface integrity.

The tool material pair method [5] is a way to optimize the cutting tool use by minimizing the required energy versus material removal rate. It has been applied to finish turning application. By measuring the cutting forces, one can calculate the specific pressure, which indicates the optimal cutting condition. It is the perfect method to compare swiftly tool geometry or lubrication performance (Fig. 4).

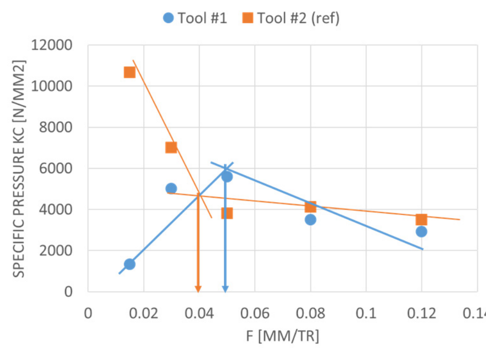

Figure 4: Specific pressure comparison for two tools geometry and according to optimal feed rate.

Concerning finishing operation, surface roughness is a very sensitive parameter for SRF application. Lubrication is a well-known key parameter. CERN has analysed various cutting fluid performance on surface roughness, as shown in the picture below (Fig. 5). Three identical parts, representative selection of the hook of the HOM coupler of the DQW crab cavity, have been milled. This complex T shape implies the use of 5- axis simultaneous machining. Same cutting parameters, tools and CNC machine program have been used.

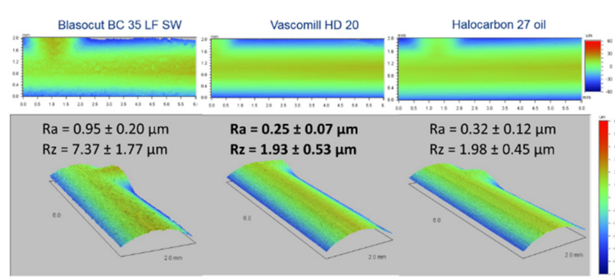

Figure 5: Surface roughness measurement on the T-shape representative test part regarding three cutting fluid.

The Blasocut™ fluid is a water-based coolant, applied through flooding the cutting zone, and is the standard coolant for all CERN applications (copper, stainless steel.). Vascomill™ and Halocarbon™ are straight mineral-based

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP061

oil, applied by spraying the part and cutting edge, especially applicable in difficult to machine material. Vascomill™ expose the best surface finish, by a factor 4 over standard Blasocut™. Halocarbon™ is also a possible solution, but more complex to use widely due to its safety issues. Finally, CERN has demonstrated that Vascomill™ is also the lubricant that leaves minimal surface pollution. Vascomill™ is nowadays the reference lubricant for Niobium finish machining at CERN main workshop.

Cryogenic CO_2 as cutting fluid is on-going development. CO_2 allows better surface roughness, without any surface pollution. Moreover, it enhances chip fragmentation, avoiding scratch issue due to normal long chips of niobium.

MEASURE AND UNDERSTAND

All the previously exposed test and optimisation have been done on past or currently produced parts. But the aim is to understand more into detail the link between machining and surface integrity. This aspect is at the heart of current research both in the industry (aeronautics, energy, automotive…) and in laboratories. It has been shown that the macroscopic friction coefficient between tool substrate and work material has a direct impact over surface integrity [6], such as grain size, heat affected layer [7] or damaged layer occurring. Impact of copper machining over niobium coated cavity performance has been started [8], and show that the right cutting condition could lead to limitation of surface and sub-surface degradation.

As a first approach, cutting force and temperature inside the niobium has been measured in an elementary cutting test. In the same time, tribological tests [9] have identified friction behaviour of the cutting oils (Fig. 6). Vascomill™ oil exposes a very low friction coefficient for low sliding speed, which could be found around the cutting edge of the tool. The shearing process might be easier thanks to lowering induced forces.

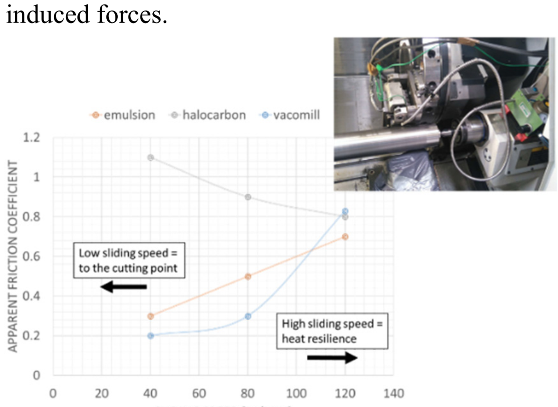

Figure 6: Evolution of apparent friction coefficient for three cutting fluid and tribometer apparatus.

Both cutting forces and friction coefficient are used to feed a numerical modelling of the mechanical and heat flux moving on the finished surface. Thus, the temperature at the surface during cutting can be estimated, including the multiple passes required to cut the entire surface (Fig. 7).

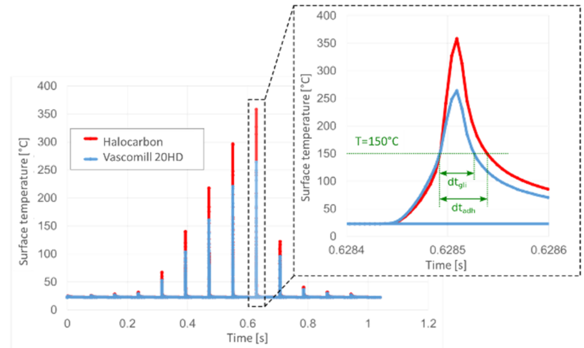

Figure 7: Evaluation of surface temperature cycles occurring during machining with multiple passes.

It appears that the niobium can locally reach up to 350 °C, and above 150 °C for around 35 µs. These first results have to be confirmed and compared to metallurgical analysis.

CONCLUSIONS

CERN has developed over the past few years extensive knowledge of niobium processing for SRF application. For the machining point-of-view, new tools and lubricant has been found and already used. Further investigation has shown the impact of lubrication mode on surface quality. At a later stage, the influence of cutting conditions over the affected surface and sub-surface would have to be tackled, based on the used methodology of coupled physical tests and numerical simulations.

REFERENCES

[1] O. Capatina *et al.*, "CERN Developments for 704 MHz Superconducting Cavities", in *Proc. 16th Int. Conf. RF Superconductivity (SRF'13)*, Paris, France, Sep. 2013, paper FRIOB04, pp. 1198-1211.

[2] M. Garlasché, "Advanced Manufacturing Techniques for the Fabrication of Hl-LHC Crab Cavities at CERN", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 409-414. doi:10.18429/JACoW-SRF2017-TUPB013

[3] M. Parise, P. Berrutti, and L. Ristori, "A New Design for the Hilumi Radio-Frequency Dipole Bare Cavity", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2659-2661. doi:10.18429/JACoW-IPAC2018-WEPMK014.

[4] S. Atieh *et al.*, "First Results of SRF Cavity Fabrication by Electro-Hydraulic Forming at CERN", in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THAA05, pp. 1012-1018.

[5] NF E66-520-1, "Domaine de fonctionnement des outils coupants - Couple outil-matière - Partie 1: présentation générale", Septembre 1997.

[6] F. Valiorgue *et al.*, "3D modelling of residual stresses induced in finish turning of an AISI304L stainless steel", *International Journal of Machine Tools and Manufacture*, 2012, Vol. 53. 77-90.

[7] F. Valiorgue *et al.*, "Emissivity calibration for temperatures measurement using thermography in the context of machining", *Applied Thermal Engineering*, 2013, 58, 321–326.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP061

[8] A. Camelin, “Approche multi-échelles de l’usinage des cavités RF et impact sur l’intégrité de surface”. Master report, 2017.

[9] C. Bonnet *et al*., “Identification of a friction model-Application to the context of dry cutting of an AISI 316L austenitic stainless steel with a TiN coated carbide tool”, *International Journal of Machine Tools and Manufacture*, 48.11 (2008), pp. 1211–1223.