Optimizing stability plots for small tools

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This project is made in collaboration with:

Funding:

INDUSTRIENS FOND

Contributors:

EDECO
EST. 1984

2 Executive Summary

To gain even better results when collecting and analysing data for tap test optimisations, this project looks into the particularities of tap testing small tools, by using TFX "Small Tools Milling". These low-diameter tools are especially interesting for medical and mould industry applications, which DAMRC in the past has limited experience with.
A comparison between "traditional milling" and "small tools" tap tests revealed an inherent pick frequency shift when changing the method. This phenomenon is corroborated by performing different milling tests and confirming the preferable method.
This report aimed to establish a relationship between pattern marks found in slot milling and chatter phenomena using microscope analysis. It was found that there was a discrepancy between microscope results, roughness measurements, and chatter. While these partial results could look like a drawback in the research, it is worth mentioning that this project's resources were not allocated to this specific task.
Finally, the outcome is a polished method, equipment, and procedure to retrieve more precise results when tap testing tool configurations below 8-millimetre diameter.

3 Introduction

Small tool milling is employed to fabricate complex shapes at high rotational speeds. One of the challenges in this process is regenerative chatter, which results in severe tool wear and reduced part quality. The associated high spindle speed causes changes in dynamics; the elastoplastic nature of these operations results in changes to the cutting coefficients. Variations in dynamics and cutting coefficients affect the stability lobes.
Tap testing is crucial for optimising machining parameters to avoid resonant conditions that can cause chatter and poor surface finishing. While tap testing is commonly used for larger tools and structures, applying it to small tools presents unique challenges but remains feasible and beneficial.
By identifying the natural frequencies and damping characteristics of the small tools and the machining system, optimal spindle speeds and feed rates can be selected to avoid resonance and chatter, leading to improved surface finishes and tool life. Properly optimised parameters reduce the dynamic loads on small tools, decreasing the likelihood of tool deflection and breakage. This is particularly important for small tools, which are more fragile. Avoiding chatter conditions results in better surface finishes and higher dimensional accuracy, which are critical in applications requiring precision machining.
Among others, we can mention three of the most important challenges. Small tools have significantly less mass and stiffness compared to larger tools, which makes detecting their dynamic properties more challenging. The precision required to measure the natural frequencies and damping characteristics of small tools is higher. Small vibrations and environmental noise can significantly affect the measurement results.
Tap testing can help in understanding and predicting the behaviour of the machining system, leading to more reliable and repeatable machining processes, especially in high-precision industries.
Assuming we have the right phenomena representation, it is necessary to create a frequency response function (FRF) model measuring the tool tip response to a known stimulus. The list of problems around this topic:

- Attaching the accelerometer in a small tool diameter (in some cases, ball-end).
- Mass/inertial accelerometer modal contribution
- Frequency excitation available power

- Accelerometer sensitivity

Our interest surrounds the strategy to overcome these difficulties. In our case, the study focuses on the use of a specific software module. This tool allows the user to attach the sensor in a different position avoiding adding mass that will affect the system.
This project studied the application of stability lobe diagrams optimising small tool milling operations in the industry. To do it, several tests were performed in-house, including the experiments and validations.

4 Pre-analysis

DAMRCS's new taptest equipment from 2023 has several new cutting modules compared to our equipment from 2010 incl. plunge Milling, Helical Milling, Trochoidal Milling, Small Tool Milling, Boring and turning. In today's taptest service at companies taptests engineers rely on the known and knowledge-transferred modules of milling, face/feed milling and turning for all processes even though other modules might have more precise results for the given application e.g., drilling processes. When browsing the different cutting modules illustrations show changes in directional parameters, units, as well as expectancy of the location of accelerators when performing the taps. Historically DAMRC has had difficulties testing smaller tools than 8 mm in diameter, therefore this project wishes to investigate the cutting module created for small tools in the MetalMax TXF software.

5 Hypothesis

There is an optimum method and setting for tap-testing small-diameter tools. The range of tools considered “small” goes from 8[mm] to 3[mm] in diameter. During this study, it is expected to define a road map for engineers and technicians to tap-test these particular tool configurations.

6 Success Criteria

The main success criteria of this project would be achieving competencies and ready-to-use procedures for tap testing small tools. Finding limitations using the current equipment, defining clear boundaries in industrial applications, it is considered as well as a project goal.

7 Project Scope/ Description

This project was primarily practical, focusing on the application of tap test techniques to small tools with diameters ranging from 3 to 8 millimetres. It did not include a theoretical exploration of micro-cutting dynamics.

8 Risk Analysis

It is uncertain if and how the hammer and accelerometer for small tools that comes with the 32-bit MetalMax equipment will perform with the 64-bit system. In the past, these hammers have been replaced by another vendor (Bruel and Kjaer). Depending on internal tests it will be decided whether the need for acquiring a small hammer and accelerometer is needed.

9 Literature Study

The most appropriate document to read was the MetalMax user manual. Unfortunately, this support does not have information regarding tap-testing on small tools (best practices, recommended sequence, parameters, etc). After requesting guidance from the MetalMax supplier, a document including a comparison, and a usage example was received [1].
Another source of information is the software itself. While recommendations are not stated, it is possible to find basic information about how the experiments should be conducted.
Inside other vendor's manuals [2], it is possible to find more information about equipment selection and limitations.

10 Experiment Design

This section was divided into two parts. A tap-testing stage where we decided and presented the test method utilised for four tool configurations. In this stage, we selected one tool and compared the direct hit method used for normal-size tools with the "small tools" method. The second part is a milling test where we adjust the machine parameters to run, first with vendor-recommended parameters, followed by a test with optimized parameters. These two tests needed a detailed preparation that we developed following.

10.1 Test design/process

10.1.1 Tool selection

Six tools were selected for the tests [Table 1]. Apart from being small-diameter tools, the selection considered two different operations, slotting, and surface finishing. Considering the small diameter characteristic, Figure 1 shows a typical geometry and its associated parameters for these kinds of tools.

Tool ID	Stickout [mm]	Cutting diameter D[mm]	Cutting length l_1[mm]	Reduced section shank diameter d1[mm]	Reduced section shank length l2[mm]	Shank diameter d2[mm]	Tool flutes Z[qty]	Nose radius R[mm]	Helix angle [deg]	Overall length L[mm]
937 0300 050 0600 080	25	3	2,4	2,85	8	6	2	1,5	30	50
F2AA0400ADL45	25	4	8	4	11	6	2	0	45	57
904 0500 050 0600 050	25	5	15	5	17	6	4	0,5	40	50
C46 0600 050 0600 030	25	6	16	-	-	6	4	0,3	40	50
UP210-SL4-04030	35	4	30	-	-	4	4	0	35	75
UP210-SL4-03015	22,66	3	15	3	18	4	4	0	35	60

Table 1 – Selected tools and their properties

Figure 1 – Typical small tool parameters

10.1.2 Tool holder selection

The tool holder was selected to facilitate the hammer hitting. To this end, the relation between the holder bore diameter and the tool shank should be as reduced as possible (see image below). It is worth mentioning that this could be a difficulty in an industrial case (where the tool holder is selected by the company).

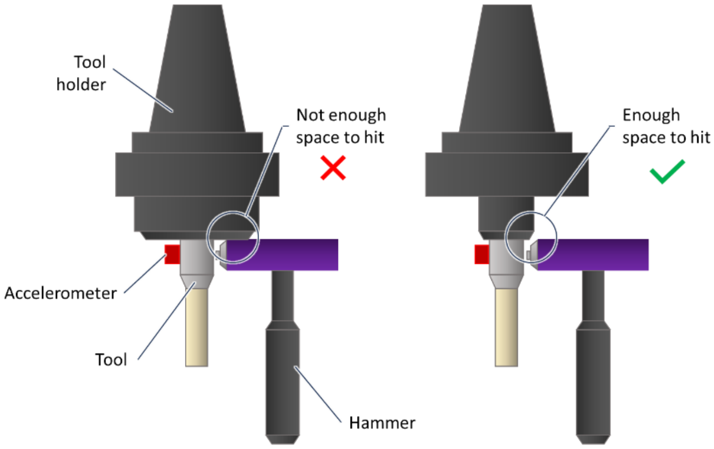


Figure 2 - Tool holder selection

10.2 Tap-Test

As it was mentioned before, three options to taptest small tools are available with our equipment.

- Direct hit: with accelerometer mounted at the tooltip and hammer hitting at the same location.
- Two measures moving the accelerometer: Direct hammer hitting and accelerometer location at the base followed by a cross-hammer hitting at the base and accel at the tooltip.
- Two measures moving the hammer: Direct hammer hitting and accelerometer location at the base followed by a cross-hammer hitting at the tooltip and accelerometer mounted at the base.

Tap tests have been carried out using DAMRC's usual procedure, just varying the sensor's placement, following software diagrams. As can be seen, the sequence starts hitting directly in the accelerometer position (“X” and “Y” directions), continuing by cross-hits in the tooltip (“X” and “Y” directions).

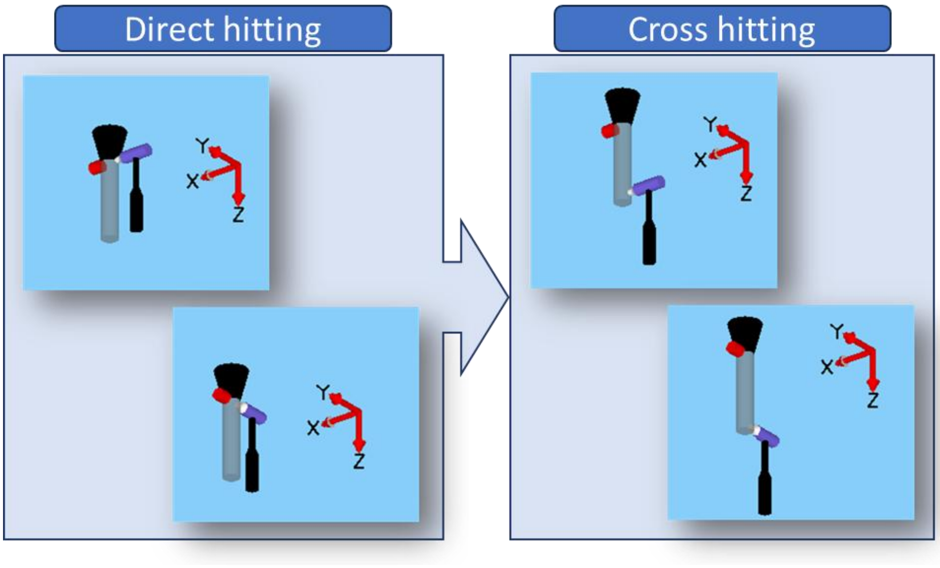


Figure 3 - Small tools module hitting process

NOTE: While the module states we should place the accelerometer in the “Holder”, after clarifying this with specialists, and according to past experiences, the right place to do it is on the tool shank, right below the tool holder.

10.2.1 Equipment for the Tap Test

For this study, we are going to use the 64-bit Tap Test equipment (2022).

- DMU 80T CNC Machine
- Torquemeter 8 [Nm]
- Tools to be tested.
- Tool holder
- Collets, 8 to 20, 12 to 20, and 16 to 20.
- 352C23 (Small 0,2g) accelerometer.
- 8206-001 (4448 N) impact hammer, Serial Number 56482.
- Data Acquisition device.
- MetalMax TXF Software.
- Test templates for each tool analysed.
- Tool stickout MetalMax Library.

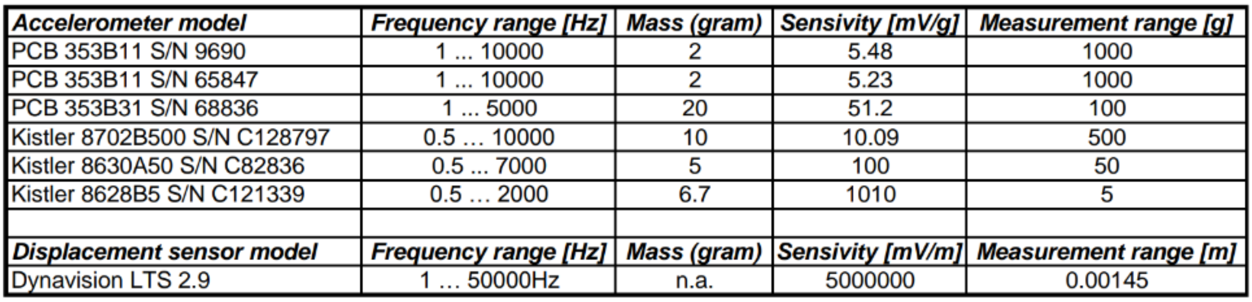
10.2.1.1 Accelerometer selection

The initial differentiator factor used for small tools is the accelerometer dimension. As we reduce the tool mass, the accelerometer should reduce proportionally to the *modal mass*, MetalMax user’s manual states it should not exceed 10% of this parameter. The modal mass is the mass participating on a particular mode, thus, is not related directly to physical characteristics. CutPro user’s manual [2] has a more practical approach and recommends a mass below 0,5 [gr] for 8mm and 6mm diameter tools.
It is important to notice that this factor is significant when placing the accelerometer on the tooltip. In this case, the used two accelerometer devices.

Figure 4 – Small accelerometer (left) [7] and medium accelerometer (right) [8]

	352C23 (Small)	352A21 (Medium)
Sensitivity (±20 %)	5 mV/g	10 mV/g
Measurement Range	±1000 g pk	±500 g pk
Frequency Range (±5 %)	2,0 to 10000 Hz	1,0 to 10000 Hz
Resonant Frequency	≥70 kHz	≥50 kHz
Broadband Resolution	0,003 g rms	0,004 g rms
Size - Height	2,8 mm	3,6 mm
Size - Length	8,6 mm	11,4 mm
Size - Width	4,1 mm	6,4 mm
Weight	0,2 gr	0,6 gr
Sensing Element	Ceramic	
Sensing Geometry	Shear	
Housing Material	Anodized Aluminium	Titanium
Mounting	Adhesive	

Table 2 – Accelerometers specifications [7][8]



Accelerometer model	**Frequency range [Hz]**	**Mass (gram)**	**Sensivity [mV/g]**	**Measurement range [g]**
PCB 353B11 S/N 9690	1 ... 10000	2	5.48	1000
PCB 353B11 S/N 65847	1 ... 10000	2	5.23	1000
PCB 353B31 S/N 68836	1 ... 5000	20	51.2	100
Kistler 8702B500 S/N C128797	0.5 … 10000	10	10.09	500
Kistler 8630A50 S/N C82836	0.5 ... 7000	5	100	50
Kistler 8628B5 S/N C121339	0.5 … 2000	6.7	1010	5
Displacement sensor model	**Frequency range [Hz]**	**Mass (gram)**	**Sensivity [mV/m]**	**Measurement range [m]**
Dynavision LTS 2.9	1 … 50000Hz	n.a.	5000000	0.00145

Table 3 - Overall sensor performances [2]

10.2.1.2 Hammer selection

As an initial selection we used the hammerfrom Brüel & Kjær type 8206. The specifications of this hammer are shown in the Table 4.

Figure 5 - Medium hammer [3]

PERFORMANCE	
Sensitivity	22,7 mV/N
Full-Scale Force Range Compression	220 N
Linear Error at Full Scale	<±1

PHYSICAL	
Overall Length	221,5 mm
Effective Seismic Mass	100 gr
Sensor Housing Material	Stainless steel (17–4 PH)

Table 4 - Hammer specifications [3]

To evaluate if the selection is appropriate and to adjust the hammer tip, we need to analyse if the expected most-flexible-natural-frequencies of the tool will fit inside the impulse curve. To get this frequency spectrum, we can take the tooth passing frequency. The following equation relates the spindle speed and the natural frequency.

$$\omega_n = \frac{N.SS.j}{60} \qquad \text{(Eq. 1)}$$

Where SS is the spindle speed, ω_n the natural frequency, N is the number of flutes and j is an integer giving all different solutions. Considering a tool with 4 flutes and a recommended spindle speed of 9000 [rpm] we would find the first mode in the area of 600 [Hz], the second one in 1200 [Hz], the third one in 1800 [Hz] and so on. While this equation gives us a good approximation to the frequency-wise range, the actual “most flexible” mode must be measured (and, in some cases, could be out of our excitement power range). By analysing the following graph, we can discard the rubber tip. While the plastic tip has a well-expected performance, it does not present good behaviour in frequencies close to 1200 [Hz]. The aluminium tip, on the other hand, can exceed those frequencies and get the hit we are looking for.

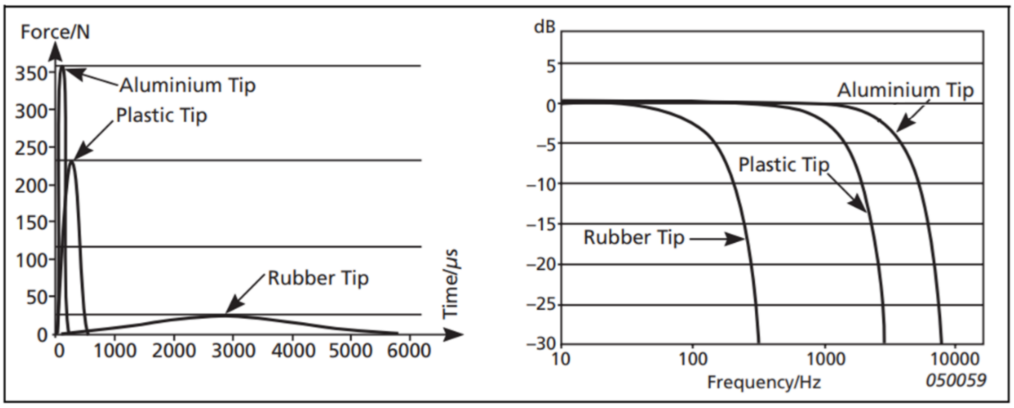
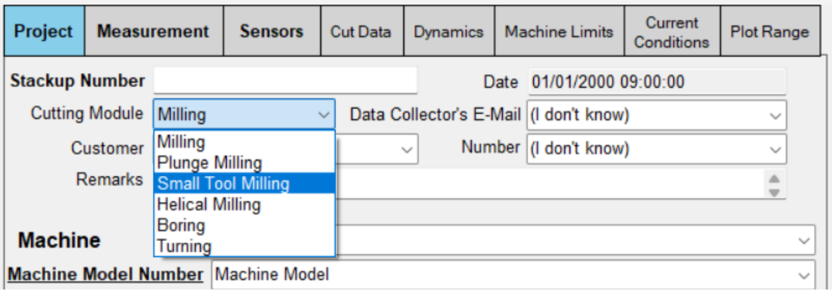


Figure 6 - Hammer tip performances [2]

10.2.1.3 Software setup

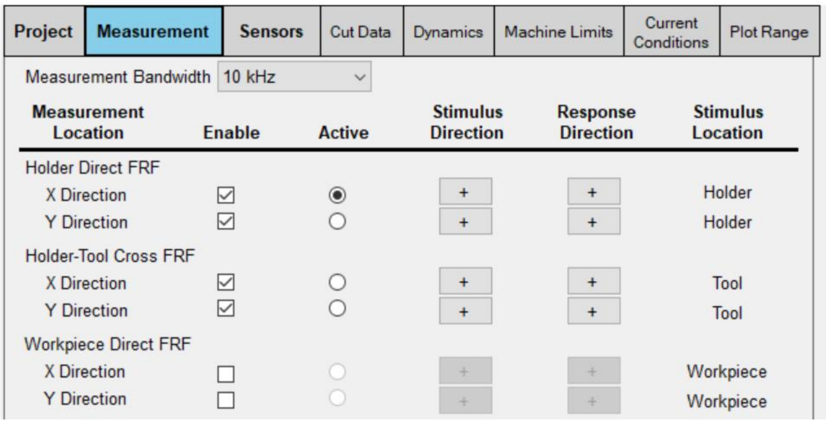
The first step is choosing the “Small Tool Milling” module from the “Cutting Module” list, located in the “Project” tab. *NOTE: depending on the TFX version it could have more cutting modules.*



Stackup Number:
Date: 01/01/2000 09:00:00
Cutting Module: Milling
Data Collector's E-Mail: (I don't know)
Customer:
Number: (I don't know)
Remarks:
Machine
Machine Model Number: Machine Model

Figure 7 - Project tab setting

Moving to the “Measurement” tab, TFX interface gives us the striking order we shall follow to get our FRF using this specific module. It is important to enable the “Holder-Direct FRF” and the “Holder-Cross FRF” (in both, “X” and “Y” directions) to properly perform the taptesting and retrieve the FRF values.

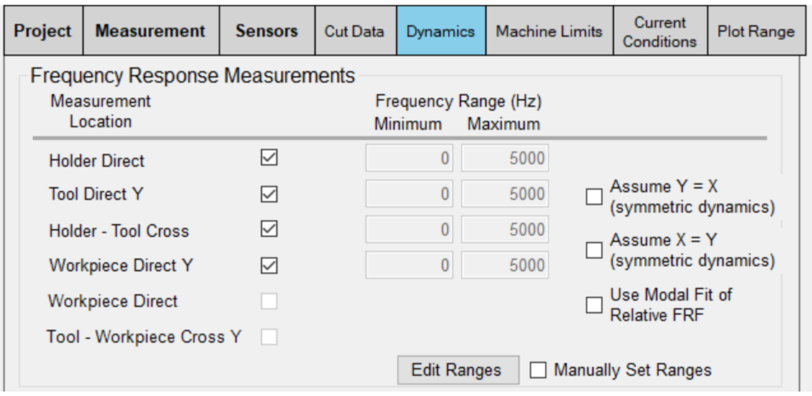


Measurement Bandwidth: 10 kHz

Measurement Location	Enable	Active	Stimulus Direction	Response Direction	Stimulus Location
Holder Direct FRF					
X Direction	☑	●	+	+	Holder
Y Direction	☑	○	+	+	Holder
Holder-Tool Cross FRF					
X Direction	☑	○	+	+	Tool
Y Direction	☑	○	+	+	Tool
Workpiece Direct FRF					
X Direction	☐	○	+	+	Workpiece
Y Direction	☐	○	+	+	Workpiece

Figure 8 - Measurement tab setting

For the system to consider the cross-hitting and perform a stability lobe diagram we need to tick manually the dynamic measurement locations “Holder Direct”, “Tool Direct Y”, “Holder – Tool Cross”, and “Workpiece Direct Y” in the “Dynamics” tab. *NOTE: This action can be done after the taptest.*



Frequency Response Measurements

Measurement Location		Frequency Range (Hz) Minimum	Maximum
Holder Direct	☑	0	5000
Tool Direct Y	☑	0	5000
Holder - Tool Cross	☑	0	5000
Workpiece Direct Y	☑	0	5000
Workpiece Direct	☐		
Tool - Workpiece Cross Y	☐		

☐ Assume Y = X (symmetric dynamics)
☐ Assume X = Y (symmetric dynamics)
☐ Use Modal Fit of Relative FRF
☐ Manually Set Ranges

Figure 9 - Dynamics tab setting

After the software setup, the taptest operator can run the tests as usual, following the software input request and procedure.

10.3 Cutting tests

These experiments aimed to find how accurate our predictions are. To do it, we ran several slot milling experiments at different spindle speeds. After analysing the surface finishing and the machine noise it was possible to identify chatter severity. Measuring chatter using visual inspection could mislead our results, so between comparable visual characteristics, the machine noise was the decisive factor.

10.3.1 Equipment for the cutting test

As it is known, the tap test results apply exclusively to a specific combination of machine-holder-tool, thus, all the milling tests will use the equipment tested in the section 10.2.1, with the sole exception of the rough material. This item was selected considering each tested tool's characteristics.

10.3.2 Material for the test

To be as precise as possible the material was selected from the list of allowable materials the tools datasheet recommends and DAMRC had stocked. Following, it is possible to see all the tool manufacturer-recommended materials.

Tool ID	Possible materials	Selected material
937 0300 050 0600 080	P M K S H	GJS-500-7C
C46 0600 050 0600 030	P M K	GJS-500-7C
904 0500 050 0600 050	P M K S H	GJS-500-7C
F2AA0400ADL45	N	Aluminium 7075-T6
UP210-SL4-04030	P M K	S355
UP210-SL4-03015	P M K	S355

Table 5 - Tools materials machinability

It was possible to find vendor-recommended parameters for each tool [4].

Tool ID	**Ap[mm]**	**Ae[mm]**	**Vc[m/min]**	**Fz[mm]**	**N[rpm]**	**Vf[mm/min]**	**Material**
937 0300 050 0600 080	≤0,15	≤0,6	70	0,019	7427	289	GJS-500-7C
C46 0600 050 0600 030	≤6	≤6	170	0,018	9018	649,3	GJS-500-7C
904 0500 050 0600 050	≤4	≤5	80	0,015	5092	305,5	GJS-500-7C
F2AA0400ADL45	≤4	≤4	500	0,020	39788	2291,8	Aluminium
UP210-SL4-04030	≤6	≤0,6	130	0,032	10350	1330	S355
UP210-SL4-03015	≤4,5	≤0,45	130	0.028	19110	2140	S355

Table 6 - Selected tools vendor's recommended parameters

Where Ap is the maximum depth of cut for the recommended parameters (slot milling) and Ae is the radial immersion (see Figure 10).

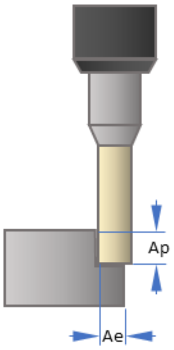


Figure 10 - Maximum depth of cut and radial immersion reference

10.4 Conduction of the test

The tap test session was carried out sequentially, using all tools suitable for cast iron machining. The same procedure was applied for aluminium and steel S355. This sequential method allowed us to save time by grouping all tap tests and milling tests on different days. Nevertheless, it is worth mentioning that the best results could be achieved when the tool is tap-tested and immediately afterwards performing the milling tests.
The standard DAMRC procedure for tap testing was followed. The hammer tip was changed from Teflon to aluminium to excite a wider frequency range while maintaining coherence between successive impacts.

11 Conclusion of the Test Results

11.1 Introduction to the test result

Tests started using the MD hammer with a nylon tip, after a couple of tests we switched to an aluminium tip. The results improved significantly. On the response side, we started using a MD accelerometer, and in order to fit inside the project scope, it was decided to continue the testing using the SM accelerometer. All these changes were documented for further comparison.
Testing a 3mm diameter tool resulted in a time-consuming effort with high deviations and errors in the process. After consulting with a specialist, it was decided to keep the results and establish a limit on the project scope on this diameter.

11.2 Conclusion on the test results

11.2.1 Tap test results

11.2.1.1 “Milling” vs “Small Tools Milling” modules comparison

In this section, we aim to establish the difference using one module or the other. This was performed on the D6 tool (C46 0600 050 0600 030).
Milling module: Using this module requires placing the accelerometer in the tooltip and performing a direct hit.

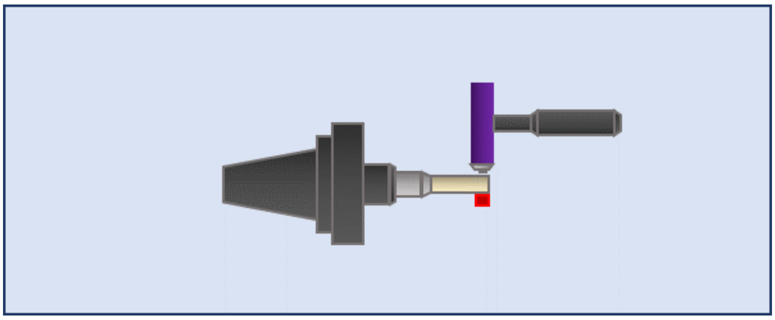


Figure 11 - Direct hitting method

When performing taptest with the milling module it was possible to see how the resulting lobe coincides with the manufacturer-recommended spindle speed. Analysing the part surface finishing we get one of the best roughness results. On the other hand, it was possible to hear a huge deal of process noise, inferring a on stable condition.

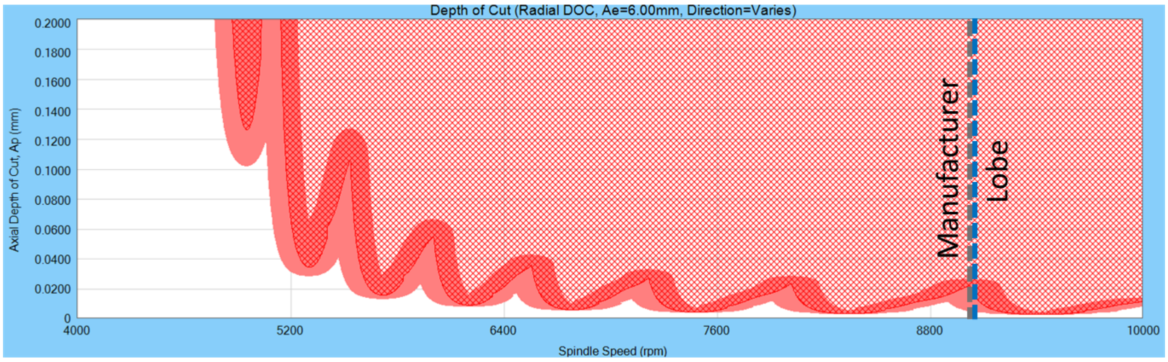


Figure 12 - Direct hitting stability lobe diagram (6mm diameter tool)

Small tools module: In this case, the accelerometer has to be placed on the tool shaft. Then two different hits are requested to complete the FRF acquisition, a direct one and a cross-hit.

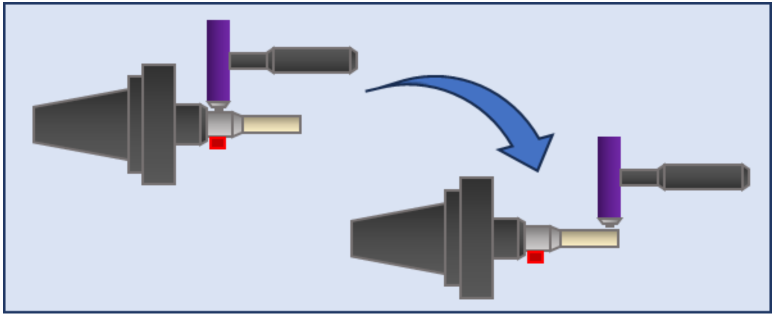


Figure 13 - "Small tools" method

We can clearly see a shift in frequencies, locating the lobes at higher spindle speeds. When testing these parameters in milling we noticed a considerable noise reduction. Unfortunately, we got an increase in roughness as well.

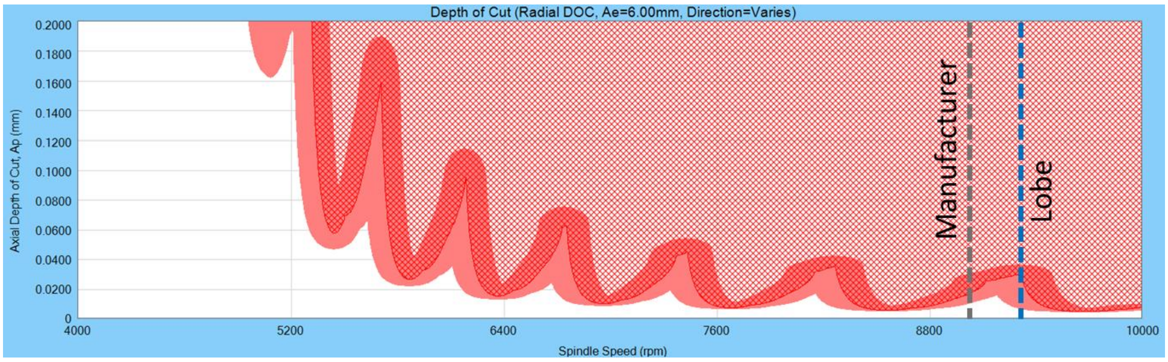


Figure 14 - Small tools hitting method resulting stability lobe diagram (6mm diameter tool)

After testing the 6mm diameter tool, we got an acceptable response. The problem arises when the stickout is shortened. As we would anticipate, the system becomes stiffer, and the natural frequencies shift to higher frequencies. When this occurs, displacements become very small and the capacity of the accelerometer to capture these accelerations decreases.

11.2.1.2 Other tool tests

Tap tests were carried out in all tool sets and notes about their performances were taken. The precision of chatter prediction varies due to different problems regarding hammer power input and accelerometer sensitivity.

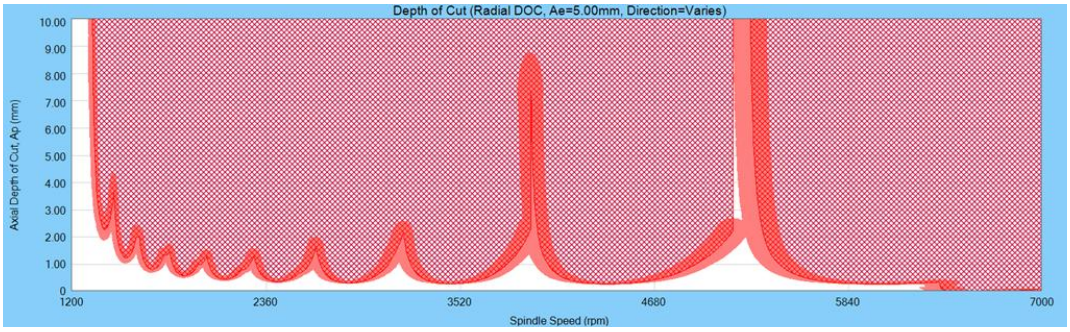


Figure 15 - Stability lobe diagram for a 5 [mm] diameter tool

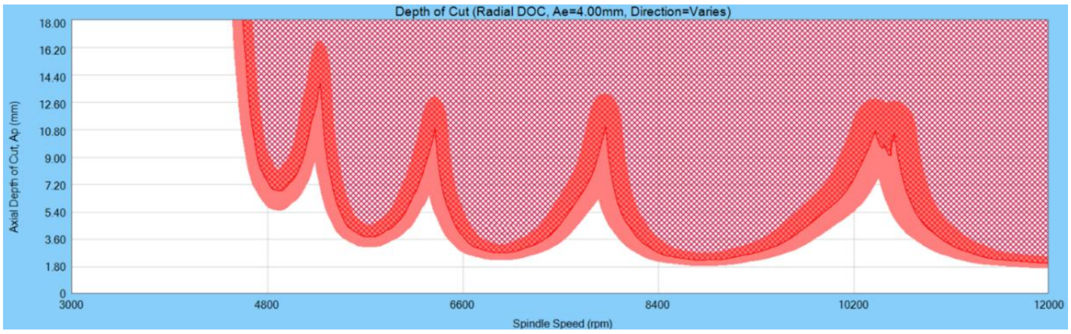


Figure 16 - Stability lobe diagram for a 4 [mm] diameter tool

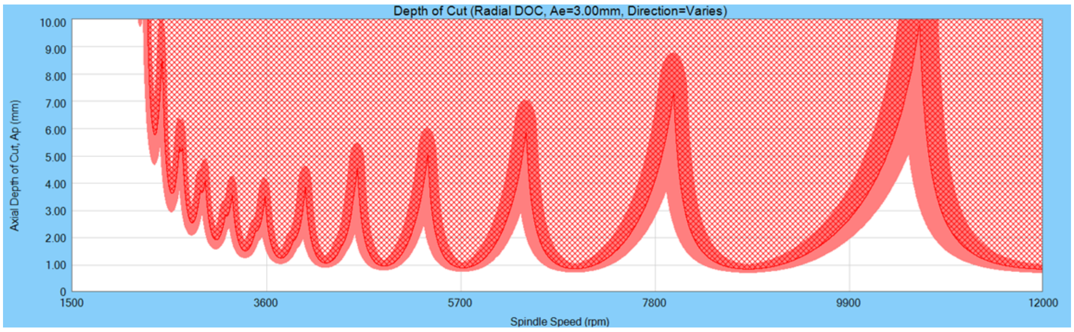
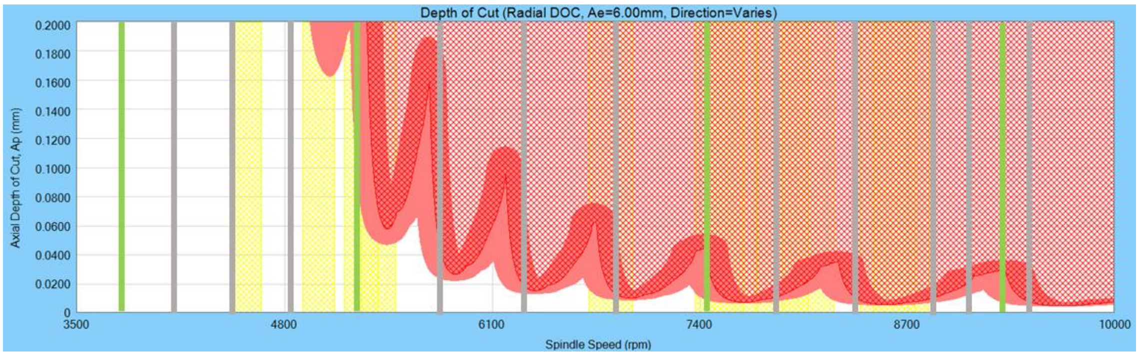


Figure 17- Stability lobe diagram for a 3 [mm] diameter tool

11.2.2 Cutting test results

A thorough cutting test was done using the 6 [mm] diameter tool. After performing tap tests, a lobe diagram was obtained for stable cutting parameters definition.



Green lines were traced at specific spindle speeds coinciding with lobe peaks. To verify the instability behaviour, other parameters (grey lines) were tested. By doing this, we can verify if the machining factors correspond with the expected stability behaviour. Special attention was paid to the vicinity of the vendor's recommended spindle speeds.

In Table 7 it's possible to see all tests performed on the 6 [mm] tool. Images taken with the microscope are presented below. Using a simple filter code, it was possible to extract the grey level for each picture. The main goal was to visually detect chatter relating the grey level measure with roughness measurements.

Ø6[mm] Endmill

Milling			*Test 1*	*Test 2*	*Test 3*	*Test 4*	*Test 5*	*Test 6*	*Test 7*	*Test 8*	*Test 9*	*Test 10*	*Test 11*	*Test 12*	*Test 13*	*Test 14*	*Test 15*	*Test 16*	*Test 17*	*Test 18*	*Test 19*
Cutting speed	*Vc*	m/min	74,08	80,19	86,29	92,40	98,39	109,21	120,02	130,83	141,65	148,72	155,81	162,90	170	177,07	191,25	205,42	170,00	173,53	177,07
Spindle speed	*N*	rpm	3930	4254	4578	4902	5220	5794	6367	6941	7515	7890	8266	8642	9018	9394	10146	10898	9018	9206	9394
Axial depth of cut	*Ap*	mm	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	6	6	6
Radial width of cut	*Ae*	mm	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Feed pr. tooth	*Fz*	mm	0,0180	0,0180	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,0180	0,02	0,02	0,02	0,02	0,02	0,02
Feed pr. revolution	*Fn*	mm/rev	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07
Feed rate	*Vf*	mm/min	283,0	306,3	329,6	352,9	375,8	417,2	458,4	499,8	541,1	568,1	595,2	622,2	649,3	676,4	730,5	784,7	649,3	662,8	676,4

Table 7 – Ø 6[mm] tool - Tested milling parameters

SS = 3925 [rpm]
DOC = 6 [mm]
Ga = 88,088
Ra = 0,701 [µm]

SS = 5220 [rpm]
DOC = 6 [mm]
Ga = 81,542
Ra = 0,672 [µm]

SS = 7600 [rpm]
DOC = 6 [mm]
Ga = 80,729
Ra = 0,856 [µm]

SS = 9018 [rpm]
DOC = 6 [mm]
Vendor's
Ga = 91
Ra = 0,813 [µm]

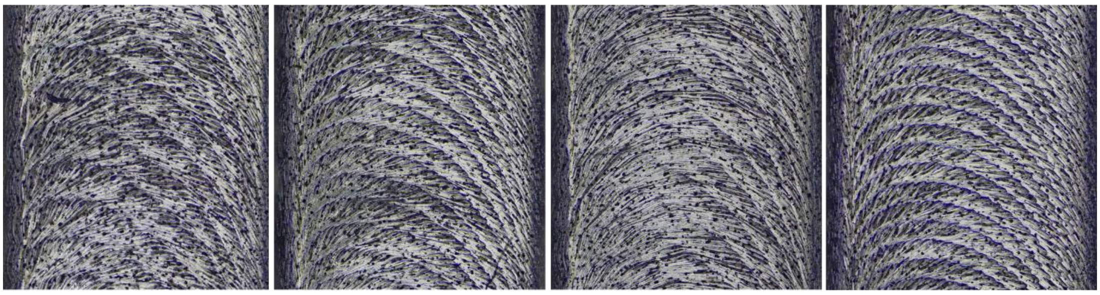
SS = 6500 [rpm]
DOC = 6 [mm]
Ga = 95,3
Ra = 1,030 [µm]

Figure 18 - Ø 6[mm] tool - Microscope images examples

Ø5 [mm] Endmill

Milling		*Vendor's*	*Test 1*	*Test 2*	*Test 3*
Cutting speed	Vc	80 m/min	82,07410808	76,96902	84,8230016
Spindle speed	N	5092 rpm	5225	4900	5400
Axial depth of cut	Ap	4 mm	4	4	4
Radial width of cut	Ae	5 mm	5	5	5
Feed pr. tooth	Fz	0 mm	0,02	0,02	0,02
Feed pr. revolution	Fn	0,06 mm/rev	0,06	0,06	0,06
Feed rate	Vf	305,5 mm/min	313,5	294,0	324,0

Table 8 - Ø 5[mm] tool - Tested milling parameters



SS = 5092 [rpm]
DOC = 4 [mm]
Vendor's
Ra = 1,247 [µm]

SS = 5225 [rpm]
DOC = 4 [mm]
Ra = 1,367 [µm]

SS = 4900 [rpm]
DOC = 4 [mm]
Ra = 0,843 [µm]

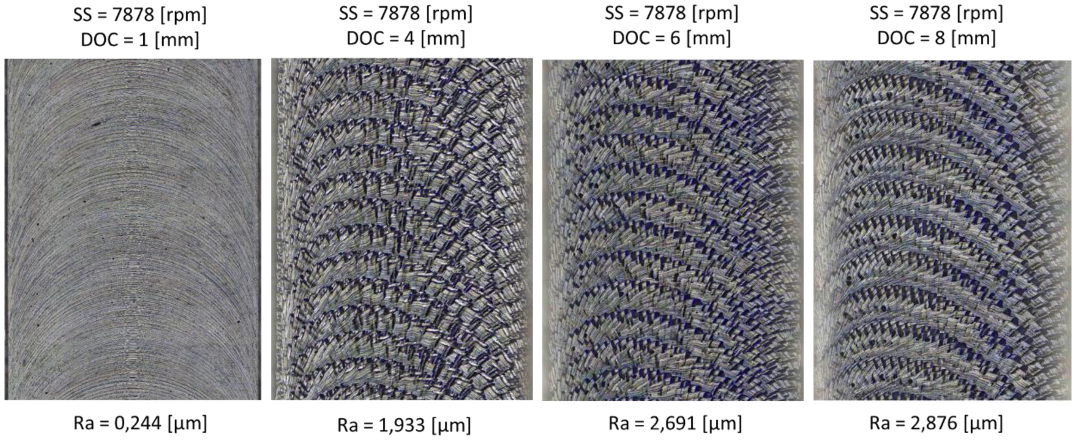
SS = 5400 [rpm]
DOC = 4 [mm]
Ra = 1,295 [µm]

Figure 19 - Ø 5[mm] tool - Microscope images examples

Ø4 [mm] Endmill

Milling		*Base*	*Test 1*	*Test 2*	*Test 4*	*Test 5*	*Test 6*	*Test 8*	*Test 9*
Cutting speed	*Vc*	87,33 m/min	99	99	99	87	99	117	140
Spindle speed	*N*	6950 rpm	7878	7878	7878	6950	7878	9348	11134
Axial depth of cut	*Ap*	4 mm	4	6	8	6	1	2	2
Radial width of cut	*Ae*	4 mm	4	4	4	4	4	4	4
Feed pr. tooth	*Fz*	0,0288 mm	0,0288	0,0288	0,0288	0,0288	0,0288	0,0288	0,0288
Feed pr. revolution	*Fn*	0,06 mm/rev	0,06	0,06	0,06	0,06	0,06	0,06	0,06
Feed rate	*Vf*	400,3 mm/min	453,8	453,8	453,8	400,3	453,8	538,4	641,3

Table 9 - Ø 4[mm] tool - Tested milling parameters



SS = 7878 [rpm]
DOC = 1 [mm]
Ra = 0,244 [µm]

SS = 7878 [rpm]
DOC = 4 [mm]
Ra = 1,933 [µm]

SS = 7878 [rpm]
DOC = 6 [mm]
Ra = 2,691 [µm]

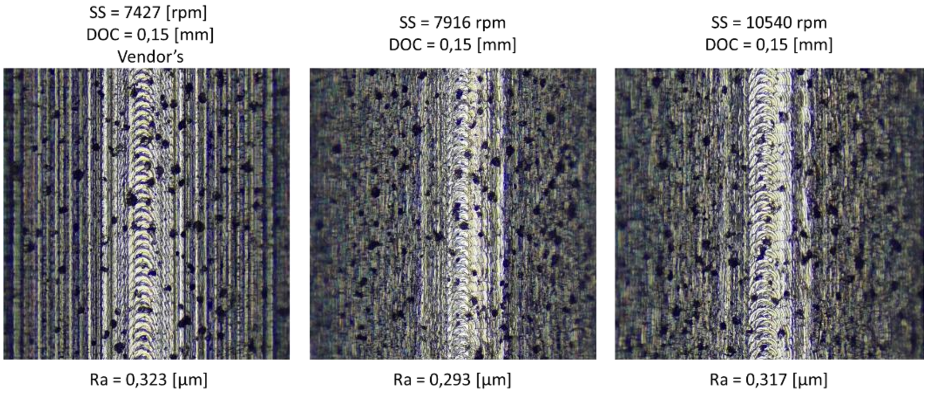
SS = 7878 [rpm]
DOC = 8 [mm]
Ra = 2,876 [µm]

Figure 20 -Ø 4[mm] tool - Microscope images examples

Ø3 [mm] Ballnose

Milling		*Vendor's*		*Test 1*	*Test 2*	*Test 3*	*Test 4*	*Test 5*	*Test 6*
Cutting speed	Vc	70	m/min	75	99	46	75	99	108
Spindle speed	N	7427	rpm	7916	10540	4850	7916	10540	11500
Axial depth of cut	Ap	0,15	mm	0,15	0,15	1,5	1,5	1,5	1,5
Radial width of cut	Ae	0,6	mm	0,6	0,6	1,5	1,5	1,5	1,5
Feed pr. tooth	Fz	0,0195	mm	0,0195	0,0195	0,0195	0,02	0,02	0,02
Feed pr. revolution	Fn	0,04	mm/rev	0,04	0,04	0,04	0,04	0,04	0,04
Feed rate	Vf	288,9	mm/min	307,9	410,0	189,2	307,9	410,0	447,4

Table 10 - Ø 3[mm] tool - Tested milling parameters



SS = 7427 [rpm]
DOC = 0,15 [mm]
Vendor's
Ra = 0,323 [µm]

SS = 7916 rpm
DOC = 0,15 [mm]
Ra = 0,293 [µm]

SS = 10540 rpm
DOC = 0,15 [mm]
Ra = 0,317 [µm]

Figure 21 - Ø 3[mm] tool - Microscope images examples

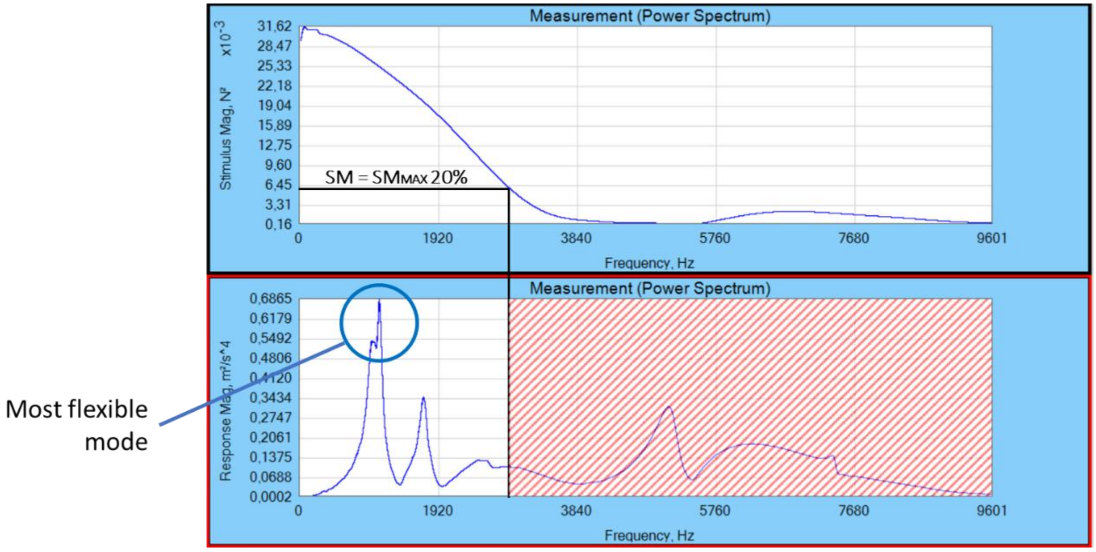
11.2.2.1 Noise analysis

While mechanical vibrations were not recorded, videos of every cutting slot were filmed to document machine noise. This is the way an operator normally "feels" the machine. Under controlled circumstances, it would lead to very accurate chatter diagnostics.
Comments were taken from the 6 [mm] diameter tool. Most of the data coincided with lobe predictions. Paying special attention to the vendor's vicinity parameters it was possible to narrow down the stability region. It was found that noise was reduced considerably around 9200 [rpm] coinciding with the stability lobe peak.

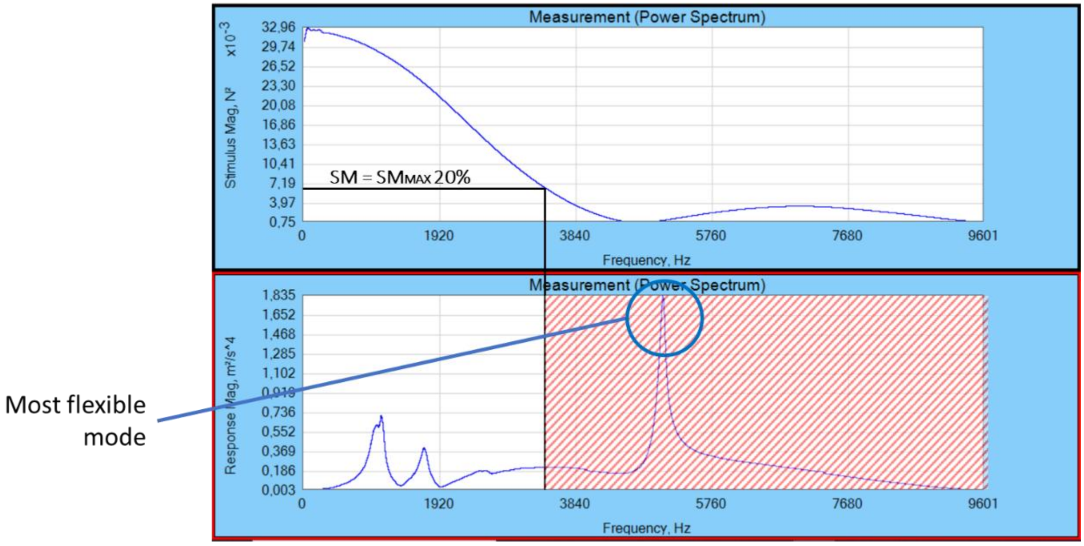
11.2.2.2 Power spectrum analysis

Depending on the tool configuration and geometry characteristics, the modal frequencies could be found on different ranges. The useful natural frequency for our analysis (the one that allows us to create the stability lobe diagram) is the most flexible one. The ability to generate acceptable results using our equipment is limited by the capacity of our hammer to excite the most flexible natural frequency with enough power. To estimate how accurate our results would be in different frequencies, it is possible to extract the power spectrum generated by our strikes.

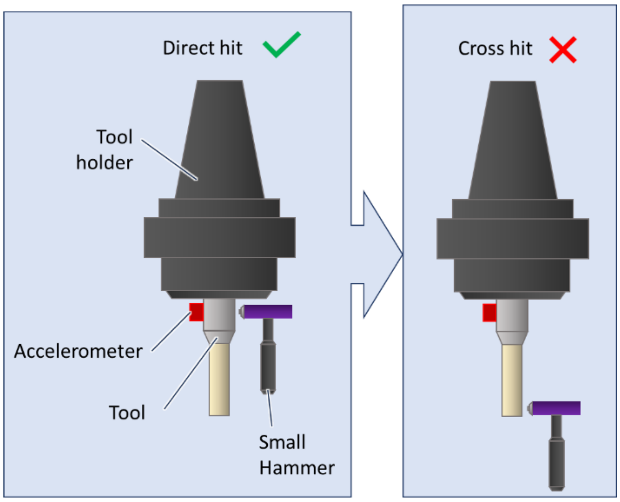
According to tap testing best practices, the results were the stimulus magnitude decreases below 20% of the maximum should not be trusted. In the following image, it is possible to appreciate a success case on a 6 [mm] diameter tool. The most flexible mode is located inside an area we consider acceptable.



On the other hand, the following image shows the power spectrum for a 5 [mm] diameter tool. As it can be seen, the most flexible mode lies in an area that should not be trusted. In this region, the hammer struck lost all power to excite those frequencies.

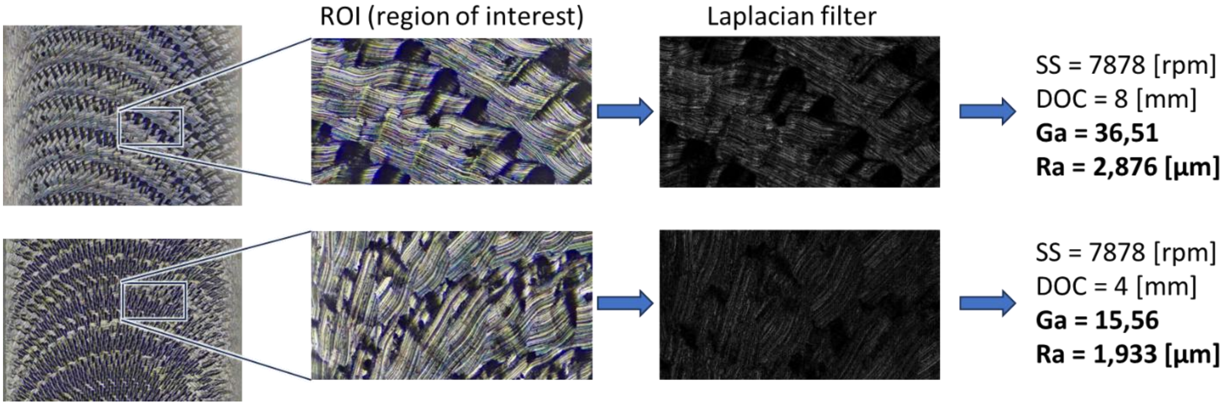


To capture these higher frequencies a small hammer is needed. During the experiments, there was an attempt to use a small hammer. Another problem appeared immediately; the sensor was unable to capture any data when the hitting was made on the tooltip (cross-hitting).



11.2.2.3 Microscope analysis

Considering the difficulty and the experience needed to detect chatter using noise records, we have allocated part of the resources to find a relationship between chatter marks and surface roughness. The basic idea is explained in [6] where the authors, using Laplacian filtering, extract a value called “grey level” from the image. This value is proportional to the surface roughness. Therefore, setting a chatter level for surface roughness, chatter can be detected by just analysing the image.



Unfortunately, we were able to find a relation (roughness/grey level) in some cases, while in others this link was not consistent. These deviations gave us low reliability ruling out the method for this report. We attribute these problems to lightning and other non-controlled experiment parameters. While the study shows certain potential is out of the scope of the project.

12 Conclusion

This project gave us a better understanding of the challenges of tap-testing small tools. The difference between traditional milling and small tool modules was determined giving a better perspective on the error margin we would have by using one or the other.
During milling tests, chatter detection was particularly challenging. Mitigation plans were developed to detect chatter in a more precise way. Using the microscope and a rough-meter it was possible to establish relations between the phenomena and the results gathered. Unfortunately, these relations were not stable making the usage improper.

A special limitation was found for some tools where the first most flexible mode surpasses the hammer power capacity to excite it.
Several tools were tested going from 6 to 3 millimetres in diameter. While the application of tap tests for small tools is limited, from all the experience gathered, it was possible to define a process and the right equipment to guarantee the best results.

13 References

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