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Cutting process monitoring with an instrumented boring bar measuring cutting force and vibration.

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Abstract

We present an industrialized version of a boring bar with embedded sensors and electronics that measure cutting forces and vibration. The novel tool gives the operator or process developer valuable insight into the cutting process in components like jet engine shafts and landing gear. Critical events like chatter and excessive insert wear can be detected and avoided and the quality of the cut can be documented and compared with earlier cuts. Since the deflection of the bar is proportional to the cutting force, the actual machined diameter is measured in real time which reduces the need for dimensional probing between cuts. In addition, the vibration measurement gives an indication of the quality of the machined surface and can reveal problematic cutting parameters or component features. We present results from machining in both Maragin 250 and steel that clearly shows the potential of the technology.

Keywords: Intelligent tools; internal turning; chatter; insert wear

1. Background and introduction

The internal turning process is inherently difficult to monitor and develop, especially for many of the large components and hard materials used in the aerospace industry. Machining deep holes in jet engine shafts or landing gear, behind closed doors in a machine tool, is a "blind" process and it can be hard to detect detrimental events like chatter, insert breakage or chip jams.

Due to its low stiffness, a slender boring bar will be inherently prone to chatter and internal damping is necessary for a stable process [1]. Even so, as the tools are getting longer, the stability margins are reduced, and it is necessary to tune the process parameters carefully to maintain stability. The stability margins can often be increased by reducing the nose radius of the insert [2], or by increasing the feed [3], but this may conflict with the surface roughness requirements or the required lifetime of the cutting edge. The typically very hard materials used in aerospace makes the situation worse.

The low stiffness of the bar will also make the process vulnerable to changes in cutting forces. The radial cutting force will deflect the bar which reduces the actual cutting depth and the resulting diameter of the machined hole [4]. Flank wear of the insert will lead to a gradually increasing radial cutting force which results in a conical hole shape.

Therefore, to develop a process that is stable with respect to chatter, insert life time, chip control, surface quality and dimensional tolerances can be both time consuming and require considerable effort.

To give insight into the process we have developed a family of slender, damped boring bars equipped with embedded sensors and electronics for measurements of cutting force, deflection and vibration. The sensor signals are communicated wireless to a client PC or Pad giving the operator and process

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developer information about what is going on at the cutting edge. It has been a major goal to deliver a robust and user-friendly product. In the process development phase, the system can be used to identify and avoid problematic features or cutting data, while in the production phase the results are used for process monitoring and documentation [5,6].

Reference [7] gives a good overview of different machining monitoring scopes and solutions. Of these, it is the prediction of tool wear that has received most attention [8]. Many of the solutions are based on measurements of either cutting force or vibration and we therefore expect that our combined solution will be able to address many of the most important monitoring tasks.

The paper presents the system in general and shows several examples of how the monitoring can be used to detect and correct various problems like tool deflection, insert wear and breakage, chip jams and chatter buildup. These are problems that will lead to dimensional errors, conical holes and surface defects.

2. System description

Figure 1 shows the damped boring bar with electronics mounted for test in a lathe. The bar is equipped with accelerometers in the front and strain gauges in the back close to the clamping area. The back of the bar is reinforced by tungsten carbide rings that also protect the strain gauges. The accelerometer signals are high-pass filtered and contain information about the vibrations of the tool tip, while the low-pass filtered strain signals are proportional to the more slowly varying cutting forces that bend the tool. Both sensor systems measure in radial and tangential directions separately. The sensor signals are transferred via cable to a battery powered electronic box that multiplexes the signals and transfers the measurement data via blue-tooth to the user software running on a Windows10 platform.

2.1. Force and deflection sensors

Both the cutting forces and the resulting tool deflection can be determined from the measured strain values. The calibration factors can be determined by loading the bar with a known force and by bending the bar a known amount using the machine tool positioning servos. The force calibration value depends only on the tool rigidity and can be factory calibrated either by loading the tool with weights or by using a force sensor.

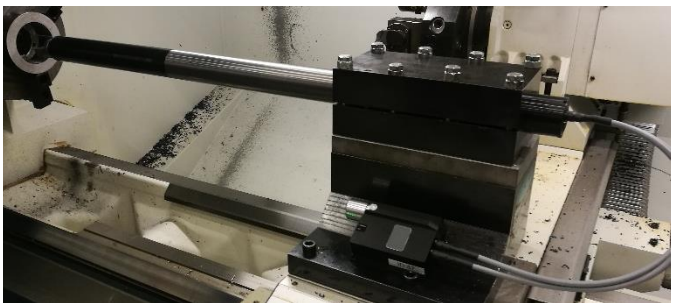

Fig. 1. The tool with electronics for wireless sensor data transfer to user.

Usually it is the resulting deviation in hole diameter and not the deflection of the bar itself that is the target for calibration. When machining, the radial cutting forces will affect not only the tool but also the clamping unit and the workpiece. The deflection of all these parts causes the hole diameter to differ from the nominal diameter during cutting. These effects can be accounted for by using the radial tool positioning servo to move the front of the tool in contact with the work piece and then continue with a stepwise bending of the tool while measuring the corresponding strain values as indicated in figure 2. From the resulting strain-position curve we can then find the calibration factor for the relationship between the measured strain and the diameter deviation during cutting.

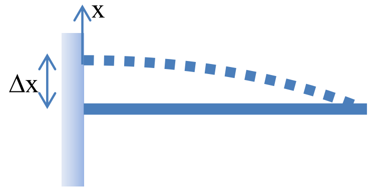

Fig. 2. Deflection calibration by stepwise bending of the tool.

2.2. Acceleration sensors

The accelerometers are of the MEMS type and can measure acceleration in radial and tangential direction from DC up to a few hundred Hz, limited by hardware filtering. The DC capability means that the sensors can measure the gravity and this is used for factory calibration of the sensitivity. This feature is also useful for tool leveling, and the user interface contains a module that helps the operator to find the right orientation of the tool with respect to the radial and tangential machine axes.

3. Measurement examples

3.1. Insert wear and chipping in Maragin 250

To illustrate the capabilities of the tool we did some test machining of Maragin 250 in the form of a scrapped jet engine shaft. The surface layer of the material is hard and abrasive (HRC50) so finding the optimal cutting parameters can be tricky. Table 1 describes a sequence of cuts with varying cutting data (Fn=feed, Apnom=nominal cutting depth, Ønom= programmed diameter, Øact=actual diameter measured by a digital caliper, Apact=Ønom-Øact, Deflect=Apnom-Apact).

Table 1. Turning in Maragin 250 with insert TR-DC1308-F, nose radius Rn=0.4 mm, cutting speed Vc=120 m/min, and initial diameter 84.5 mm.

Cut	Fn *(mm/r)*	Apnom *(mm)*	Ønom *(mm)*	Øact *(mm)*	Apact *(mm)*	Deflect (mm)
1	0.2	1	86,5	85,8	0,65	0,35
2	0.2	1	87,8	86,85	0,52	0,48
3	0.16	1	88,85	87,8	0,48	0,52
4	0.16	0.7	89,2	88,75	0,48	0,22
5	0.12	0.7	90,15	89,72	0,48	0,22
6	0.12	0.5	90,72	90,3	0,29	0,21
7	0.08	0.5	91,3	90,89	0,30	0,20
8	0.08	0.3	91,49	91,18	0,14	0,16

All cuts in table 1 were made with a TR-DC1308-F insert with nose radius $R_n=0.4$ mm at cutting speed $V_c=120$ m/min. When in cut, the radial cutting force will deflect the tool and cause the diameter of the machined hole to be smaller than the programmed diameter. Since the deflection of the tool is measured using the strain gauges we know the position of the insert edge and therefore also the resulting machined diameter. The measurements corresponding to the 8 cuts in table 1 are shown in figure 3. The insert enters the cylindrical work piece at z=0 and exits at z=33 mm. Since the nominal diameter of cut1 is 86.5 mm the plot starts at this value but as the insert engages the work piece, the diameter changes due to the deflection. This cut also shows an accelerating deflection which is characteristic for increasing insert wear.

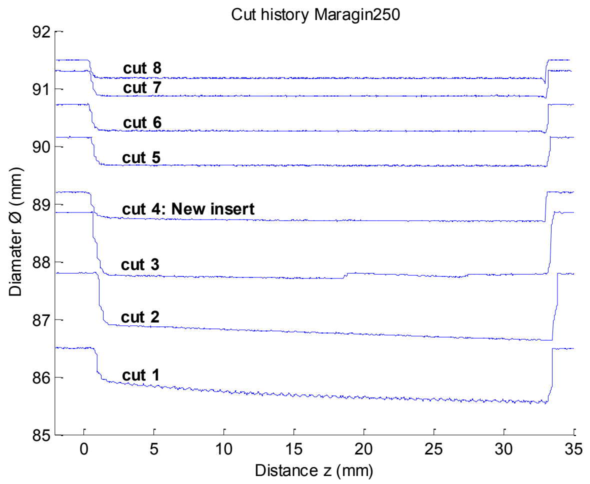

Figure 3. The measured diameter for the sequence of cuts in table 1.

Figure 4 shows the recorded tangential and radial cutting forces for cut 1, and we see that as the wear develops, the radial force increases, while the tangential force is reduced due to the increased deflection. The oscillation in the tangential signal is caused by a slightly varying cutting depth caused by imperfect centering of the rotating work piece. This offset is almost removed in the first cut.

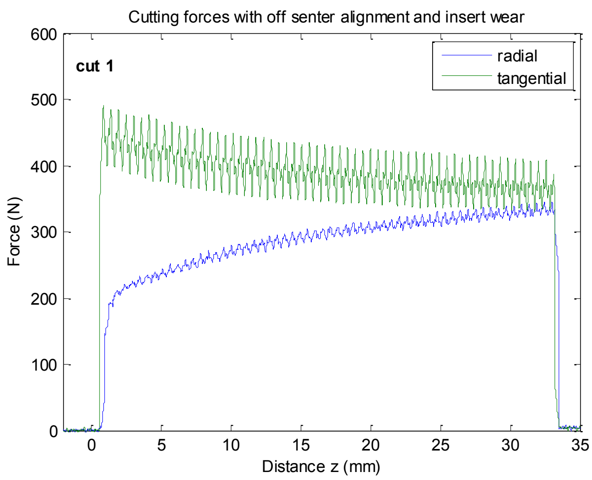

Figure 4. Measured tangential and radial cutting forces for cut 1.

The insert wear continues in the next cut and at the start of cut 3, the radial cutting force is larger than the tangential as shown in figure 5. This is not a normal situation for the selected cutting parameters and eventually, 17mm into cut 3, we get a chipping of the cutting edge. This leads to a sharper edge that cuts slightly deeper which causes a sudden drop in the radial force and a corresponding increase in the tangential force.

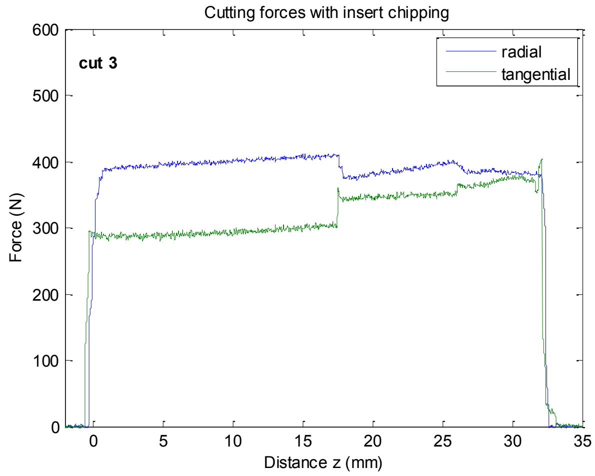

Figure 5. Measured tangential and radial cutting forces for cut 3.

After changing insert and reducing the cutting depth and feed we get a more stable situation as shown in figure 6.

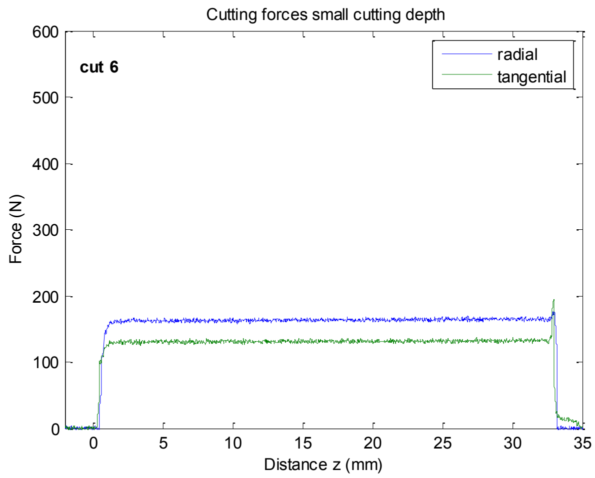

Figure 6. Measured tangential and radial cutting forces for cut 6.

3.2. Profiling in steel

Another interesting application for a measuring tool is to find the effect of the varying cutting conditions in different positions along a profile. In the programmed profile shown in figure 7, the engagement angle of the insert and the resulting chip flow will change along the profile. This will cause the radial cutting forces to change as well, and the machined profile will therefore differ from the programmed. The cut starts at z=0 and proceeds towards the left in the graph. The nominal cutting depth is 0.5 mm all along the pre-machined profile. The upper plot shows both the programed path and the actual path of the tool tip. The lower plot shows the difference caused by the tool deflection. Knowing the difference makes it possible to tune the process and implement compensation schemes.

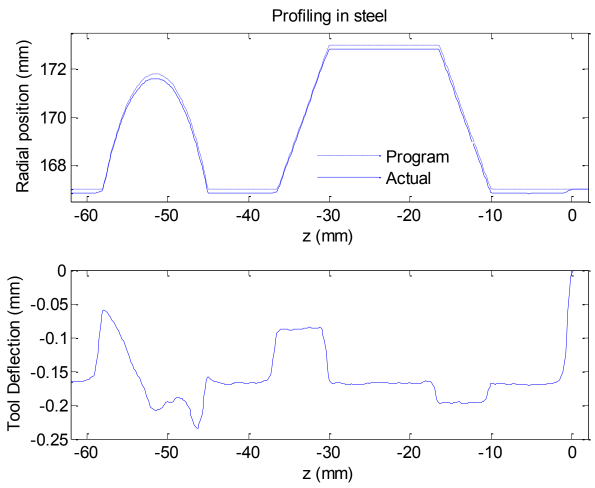

Figure 7. Results from a profiling operation in 34CrNiMo6 (HRC 34). The deflection causes the actual diameter to differ from the programmed. The difference varies along the profile due to changing cutting conditions.

3.3. Detecting vibration level and chatter

Regenerative chatter is often the factor that limits the boring operation. It is well known that long tools are problematic and internal damping is necessary but not always sufficient to obtain a stable operation. Usually it is the finishing operation, where the cutting depth and feed is small that is most critical with respect to chatter. Increasing the feed or reducing the nose radius of the insert will often help to suppress chatter but this will also worsen the theoretical surface roughness. Due to this tradeoff between stability and surface finish it is often desirable to operate close to the stability limit, which means that if the material properties vary, the same cutting parameters can be stable in one component and unstable in another. Detecting chatter at an early stage is therefore very interesting for the operator.

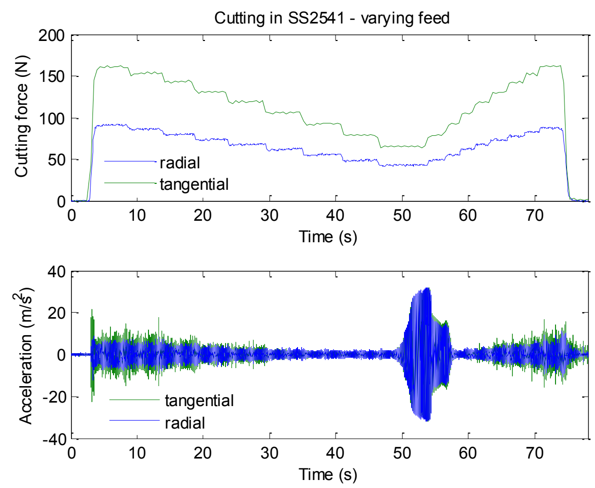

Figure 8. Cutting in steel with a feed that is reduced from 0.1mm/r to 0.02mm/r in steps of 0.01mm. a) Cutting force, b) accelerometer signal.

Figure 8 shows a test cut in 34CrNiMo6 (HRC 34) with insert DCMT04-PF, cutting speed V_c=200 m/min and cutting depth a_p=1 mm. The feed is manually reduced from 0.1 mm/r to 0.02 mm/r in steps of 0.01 mm/r. The cutting forces in figure 8a) are gradually reduced because of the reduced feed. The accelerometer signal in figure 8b) clearly shows that the vibration level is also gradually reduced until chatter starts to build up at low feed and dies out when the feed is increased again.

By fourier transforming the accelerometer signal we can monitor the frequency spectrum and warn the operator if a chatter vibration starts to build up. The measurement is very sensitive and will react long before the chatter can be heard or seen as a surface defect.

4. Conclusion and further work

We have presented a damped boring bar with embedded sensors that targets the most important deviations in the internal turning process. The focus of the paper is to highlight some of the possibilities that lies in this technology without going into too much detail. Work is now ongoing in developing and implementing signal processing algorithms that can provide information at a higher level than the measurement data we have shown here. The intention is to continually improve the user value by implementing new process knowledge into smart algorithms that provide the operator with high quality information about the events that takes place inside the machined component.

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