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Observations of surface acoustic wave strain and resistive strain measurements on broaching tools for process monitoring

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Abstract

The monitoring of high end material removal processes continues to develop to greater levels of technical sophistication which in turn enable greater levels of insight into the process phenomena occurring at the tool-chip interface. The broaching process is a traditional machining process which is used extensively in the manufacture of some of the most expensive components of the aero engine. As a relatively slow cutting process with low degrees of freedom, broaching could be a target for strain based monitoring. It is well known that strain gauges provide a rich source of data when installed close to the cutting process. This research provides insight into the resistive strain gauge measurements during broaching. The paper also specifically focuses on the use of surface acoustic wave based strain measurement and provides some initial observations on the strain data available during tooth loading and cutting scenarios in broaching.

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Keywords: broaching tooth; strain field; monitoring

1. Background

The topic area of sensors and monitoring in machining processes has been recently reviewed by Teti et al[1] providing a comprehensive body of information on the state of the art ranging from sensor systems to signal processing and decision making algorithms. However the use of monitoring in broaching processes is a relatively limited despite the critical nature of the broaching of aero engine components such as fir-tree slots. Monitoring of aero engine manufacturing processes has received renewed attention in recent years by researchers such as Klocke et al[2] and Veselovac[3] who have strong collaborations with aero engine component manufacturers.

Axinte et al[4] also carried out significant research on the monitoring of broaching processes where a variety of sensors were applied to a servo-hydraulic broaching machine including acoustic emission, vibration, cutting forces and hydraulic pressure. The authors demonstrated good correlation between defects in the broaching process and acoustic emission, vibration and cutting forces and ranked the sensors in order of the ability to detect tool condition with combinations of time and frequency analysis of the sensor signals.

Of particular interest in broaching is measurement of cutting forces and this has involved the development of special purpose workpiece fixtures that have been combined with various force sensor systems [2]. The platform provides essential data for validation of models of forces in broaching such as the work reported by Vogtel et al[5]. With the renewed interest in the modeling of the broaching process [5-7] there is a requirement for novel approaches for the validation of the models with accurate measurements.

Up to this time there has been relatively little focus on the strains and forces experienced on the tool side of the broaching process. Axinte et al[8] investigated the monitoring of various broaching tool profiles with forces, vibration and acoustic emission, but the focus was on the workpiece. Monitoring forces and strain on the tool side is challenging due to the motion of the broaching tool, limited access to the

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broaching tooth, and the complex tooth profiles. This research paper proposes an approach for strain based measurement on the tool side using both wired resistive strain gauges as a reference, and novel wireless Surface Acoustic Wave (SAW) based strain sensors.

Figure 1 below illustrates the SAW sensor concept. An incident short duration RF signal is transduced into a surface acoustic wave which propagates along the surface of the device setting up a standing wave and causing the device to resonate at a so-called centre frequency. Mechanical strain modulates this centre frequency. An RF interrogator is used to supply both the energizing RF pulse and detect the change in the resonant frequency of the SAW device.

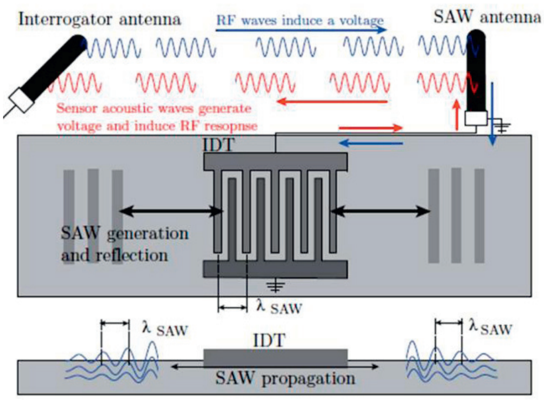

Fig. 1. Typical SAW sensor layout showing concept [9].

In the past there have been limitations with integrating SAW sensors into applications, primarily due to a lack of commercially available interrogation systems. However commercial off-the-shelf solutions for temperature monitoring in high end applications such as turbine blade are now available. Up to now strain measurement using SAW devices has been largely confined to the research domain possibly approaching TRL 6 to 7.

Recently work by Stoney et al[9] demonstrated the principle that surface acoustic wave strain based monitoring of turning processes is possible. Further work demonstrated real time measurement of strain up to 240Hz [10].

Through appropriate miniaturisation and integration SAW sensors can be positioned close to the cutting action in order to wirelessly measure strain. Monitoring of the cutting process in broaching has the potential to detect critical tool conditions that may cause issues with workpiece sub surface integrity leading to potential failures of the part in service. Wired strain measurement solutions have limitations and disadvantages in the industrial implementation due to specialist effort to protect and route cables in the harsh environment of broaching. This paper reports on the first work using wireless SAW strain sensors in the broaching process aimed at overcoming the drawback of wired sensing solutions.

2. Experimental approach and setup

A broaching analogous process was set up in order to facilitate measurement using a Kistler dynamometer type as shown below.

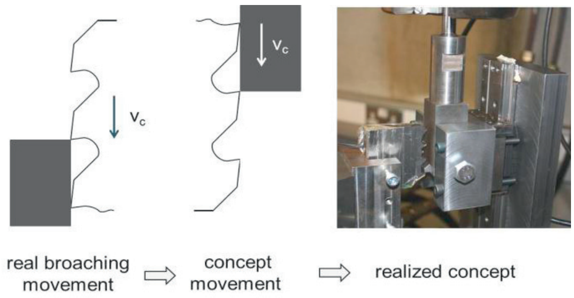

Fig. 2. Broaching analogous process for measurement of force and strain during broaching.

It can be seen that the analogy involved the movement of the workpiece sample relative to a stationary broaching tool in order to facilitate measurement of forces experienced by the broaching tool. An Instron 8874 multiaxis servo-hydraulic loading machine type was used to provide the force and movement in the vertical axis. Rigid tool and workpiece clamps and precision linear guideways were manufactured for the test scenario.

A generic measurement chain for high speed data acquisition was reconfigured for the purpose of monitoring sensors signals from the Kistler dynamometer, the resistive strain gauges, and the SAW strain sensors. Figure 3 shows the measurement chain for the experimental setup using National instruments C-DAQ hardware.

The Kistler type 9263 dynamometer was connected via charge amplifiers to the analogue input card type C-DAQ 9239. The wireless SAW sensors were connected through an interrogator and sampled at 45Hz with one additional option for higher sampling at 5kHz through an analogue input channel.

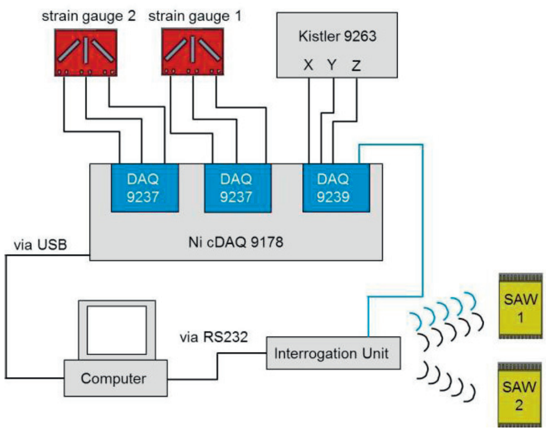

Fig. 3. Schematic of the measurement chain showing Kistler, Strain and wireless channels.

The sample rate for the strain gauge measurement was 5kHz. Two different test configurations were tested in order to quantify the strain measured on the broaching tool tooth, and strain measurement in the broaching tool structure.

2.1. Sensor installation

A broaching tool type PMT 15 made from HSS- 67HRc was selected, cut into two segments and instrumented to measure strain on the tooth and strain in the tool structure. Resistive strain measurement using a strain gauge rosette and SAW based strain measurement sensors were applied in both cases. The Figure below shows the rosette strain gauge integrated on the rear face of the tooth of the broaching tool segment, and similarly the mounted SAW sensor can also be seen integrated on the last tooth of the broaching segment.

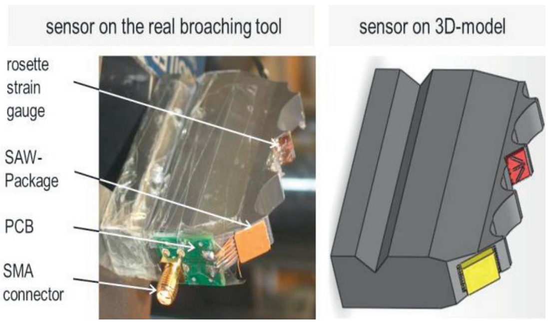

Fig. 4. Image and illustration of the strain rosette and the packaged SAW sensor mounted on the rear face of two teeth on a broaching tool segment.

The resistive strain gauge rosette rectangular 45° type was orientated to measure the strain in the single principal direction, and therefore required hardwiring to the C-DAQ 9237 amplifier unit. The SAW sensor was also oriented in the principal strain direction on the back of the tooth. The package of the sensor can be clearly seen in Figure 4, and the coupling between the SAW sensor and the antenna was enabled through a wirebond between the SAW die and the package, and then to subsequent surface mount connections on the PCB as shown in the Figure 4.

Loading and calibration was performed in stepwise manner on the strain gauge instrumented tooth and on the SAW sensor instrumented tooth respectively using ISO 7500-1 guidelines. The force was applied in the Kistler oriented *Y* direction- as a vertical applied load up to 1.5kN. The response from the sensors is shown in Figure 5.

It can be seen there is strong correlation between the load applied and the strain and SAW sensor output. The strain shows a magnitude of 3000 micro strain which is close to the allowable limit of this particular strain gauge. The voltage output from the SAW sensor interrogation system shows a linear correlation with stepwise loading applied by the Instron and shown on the Kistler dynamometer. Subsequent analysis of the relation between applied load and recorded strain revealed an R-squared value of 0.99 in the case of the strain gauge and 0.98 in the case of the installed SAW sensor.

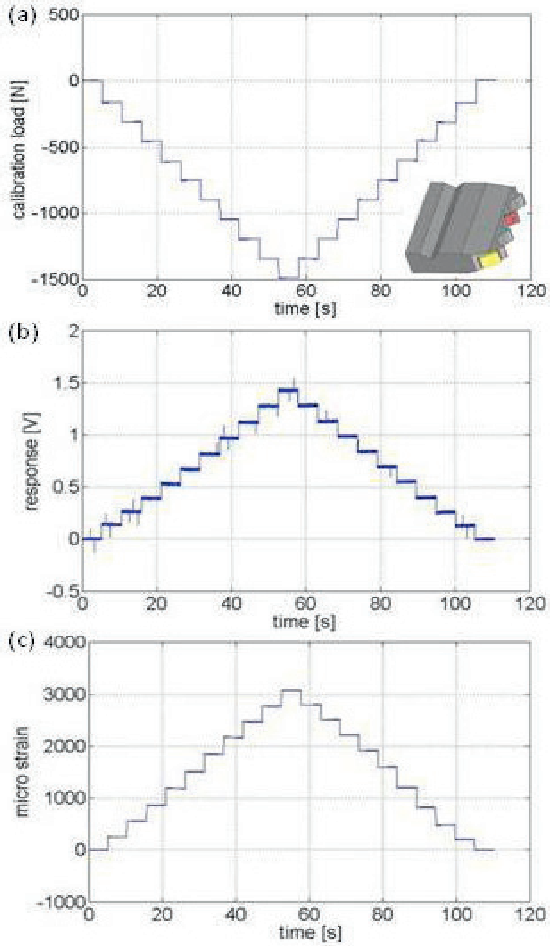

Fig. 5. Calibration data for tooth mounted sensors; (a) Kistler dynometer; (b) SAW strain sensor; (c) resistive strain gauge output.

Further analysis revealed hysteresis of 1.5% on the SAW sensor, and 8 % on the resistive strain sensor. It can be seen that the tooth mounted strain measurements during this loading regime provide clear measureable phenomena in both resistance and SAW strain sensors. With appropriate packaging and miniaturisation it may be possible to have a tooth mounted wireless strain measurement during the broaching process.

Due to the obvious issue with gaining access to the rear side of the broaching tooth, a second configuration of strain measurement was selected based on quantifying strain in the main structure of the broaching tool. The second configuration of the instrumented broaching tool involved the application of strain gauge pairs including two resistive strain gauge rosettes, and two SAW strain sensors to the structure of the broaching on opposing sides of the tool. Figure 6 shows the sensor locations relative to tooth number for comparison of applied loads.

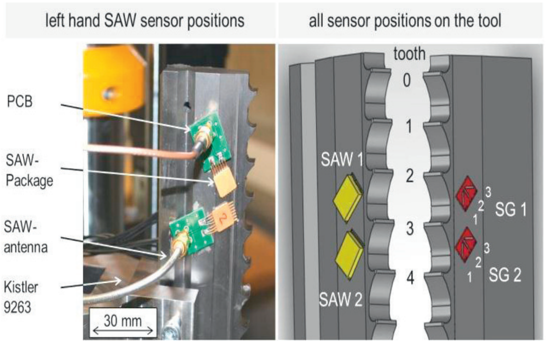

Fig. 6. Image of the SAW strain sensors integrated on one side of the broaching tool, and illustration of the opposing pairs of SAW's and strain resistive strain sensor.

It can be seen that the strain gauges were mounted on opposite side of the cutting tool in order to facilitate a comparison between the resistive strain and SAW strain sensor performance. The orientation of the sensors was selected based on other analysis work undertaken to identify the main directions of strain and how those directions change during the broaching process. The Figure below shows the main strain orientations in the diagram where Θ = the angle from the principal direction to the reference grid, and Φ = the angle of the whole strain gauge to the global coordinate system. ε_n is the strain value recorded on the DAQ for strain channel n.

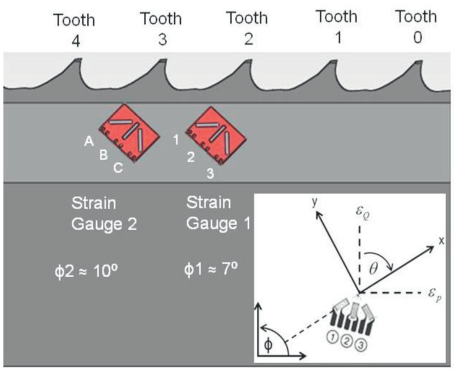

Fig. 7. Image of the rosette strain gauges and relative orientations to global coordinates.

From Equation 1 the strain direction can be inferred from the measured data. The principle strain magnitudes were calculated from Equation 2 below.

$$\theta = \frac{1}{2} \cdot \tan^{-1}\left(\frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3}\right) \quad (1)$$

$$\varepsilon_{P,Q} = \frac{\varepsilon_1 + \varepsilon_3}{2} \pm \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \quad (2)$$

The load applied on the tooth 3 is shown in the Figure below recorded on the Kistler dynamometer, SAW sensor 2, and resistive strain gauge 2.

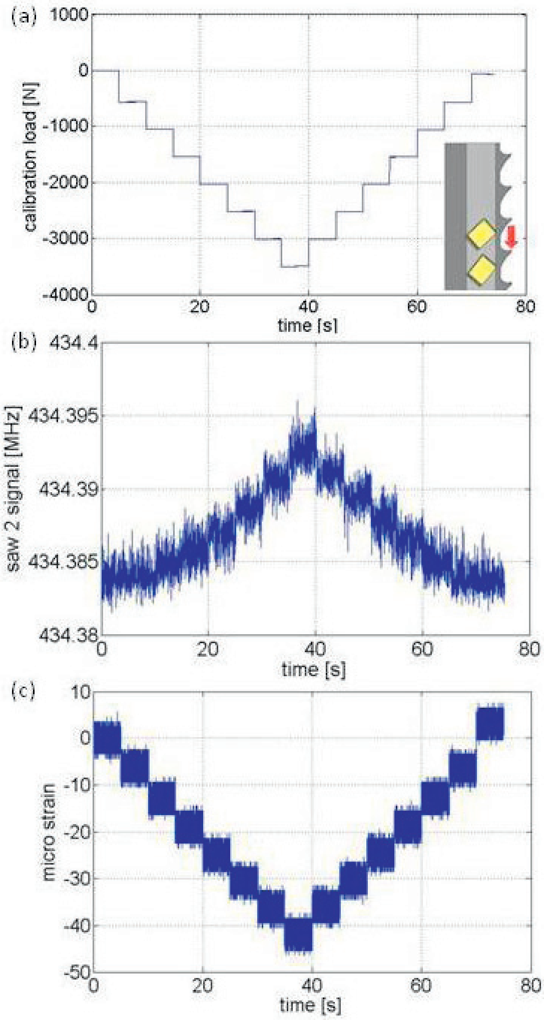

Fig. 8. Calibration data for side mounted sensors; (a) Kistler dynamometer; (b) SAW strain sensor; (c) resistive strain gauge output.

It can be seen that there is good agreement between the strain sensors at position two for the loading cycle up to 3.5kN. It is notable that the SAW sensor output is low for the applied load showing only a centre frequency change of approximately 10kHz for load of 3.5kN. It has been reported previously that the strain sensor is sensitive to alignment with principal strain direction. The high dynamic content of the SAW sensor output is attributed to features with the interrogation algorithm and requires further improvement.

3. Results during cutting investigations

Observations of the signals recorded on the single cutting tooth strain during initial cutting investigation on D2 tool steel 62HRc are shown in the Figure below. The cutting speed was 0.5m/min and ideal depth of cut of 65 micron equivalent rise per tooth (RPT).

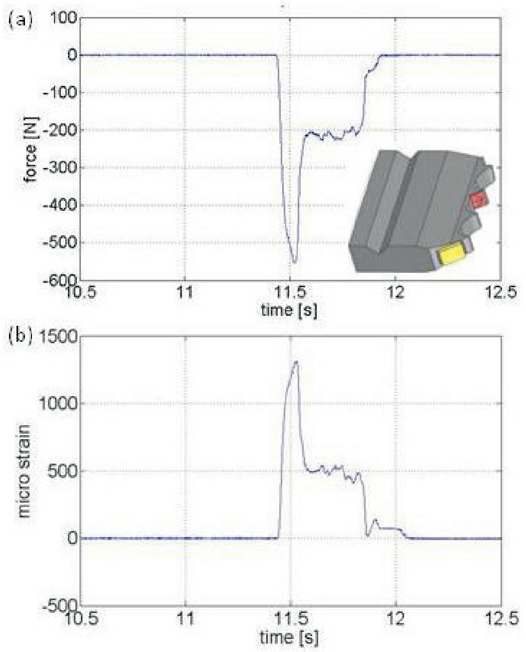

Fig. 9. (a) Kistler dynamometer *Y* axis; (b) rosette strain gauge on tooth.

It can be seen that there is good agreement between the load signals recorded on the Kistler dynamometer and the strain recorded on the rear of the tooth. The *Y* axis represents the feed direction, although there was a force component recorded in the normal direction, and the cutting force is the resultant of the feed and normal forces. The peak in the early phase of cutting represented the initial contact and the partial tooth engagement for the following 0.2s, the following region at the lower steady state is hypothesised to represent a reduced engagement condition due to lack of stiffness of the test rig in the direction normal to the feed direction. It is noteworthy that the agreement between the signals has an R-squared value of 0.98. A region from $11.9<x(t)<12.1$ in the resistive strain sensors shows a feature that was attributed to contact between part of the actual resistive gauge and the rear of the broaching tool following the cutting process.

Figure 10 shows the equivalent response from the SAW sensor on the tooth during cutting of D2 steel, compared with the Kistler recorded load in the *Y* vertical direction in the same Figure. It can be seen that there is a modest peak on contact and early cutting and in agreement with the observations during the strain tooth cut, it can be seen that the engagement changes. It is notable that the overall magnitude of force sensor output is lower than the earlier case, and again this is attributed to lower engagement and also issues with stiffness of the experimental rig. Video evidence from the cut supports the hypothesis that there are stiffness issues with the current version of the test set-up. A main characteristic of the observations in Figure 10 is that there is good agreement between the Kistler sensor output and the SAW sensor output.

The tooth based strain measurement with the wireless SAW sensor shows good potential for measurement and monitoring purposes.

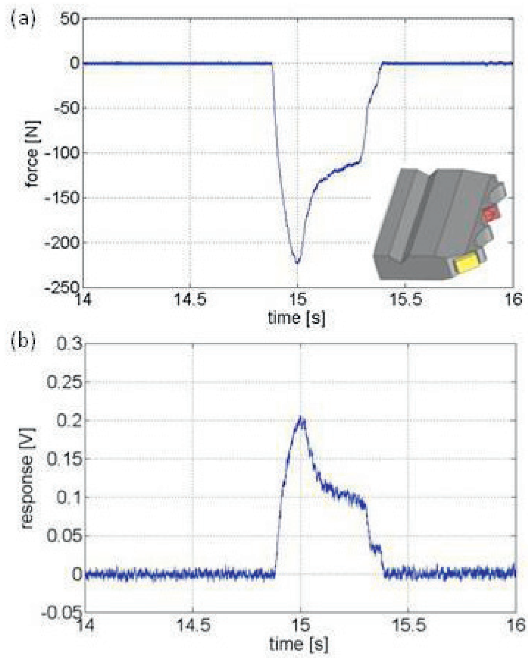

Fig. 10. (a) Kistler dynamometer *Y* axis, (b) SAW strain sensor on tooth.

With suitable miniaturisation of the SAW sensor packaging, and appropriate integration of the antenna, the SAW sensor could be applied to more complex broaching tool geometries in order to provide quantitative evidence of strain and provide validation for modeling work.

Figure 11 shows output from the Kistler sensor, the SAW strain 2 sensor, the strain gauge 2 mounted on the structure of the broaching tool when the tooth 3 is cutting D2 steel. It can be seen that the strain measurement is in the region of 10^1 microstrain measured on the structure of the broaching tool in contrast to the 10^3 microstrain levels on the rear of the tooth face. It can be seen that there is overall agreement between the resistive strain gauge 2 and SAW strain 2 sensor output. This result is better than expected considering that the SAW strain sensor is sensitive to strain field direction and is not expected to fully represent the moving strain field that exists during cutting. This indicated that other work undertaken to identify a suitable location with uniform strain field was relatively accurate. The results reported in the paper show the first experiences of wireless strain measurement using SAWs on broaching tools and it can be seen that further work is required to examine technical aspects in greater detail.

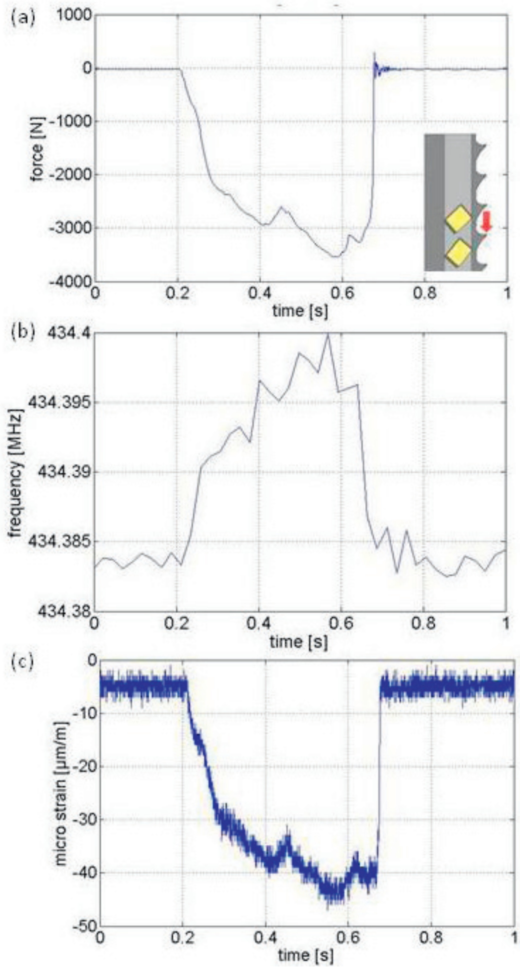

Fig. 11. (a) Kistler dynamometer *Y* axis; (b) SAW strain sensor 2; (c)resistive strain gauge output on the structure of the broaching tool during single tooth engagement in D2.

4. Conclusions

Measurement of forces and strains during broaching has the potential to provide significant insight into opportunities for tool optimization, and facilitate monitoring and potential adaptive control of the broaching process. Strain based measurement of broaching has received relatively little attention in the scientific literature. In particular wireless strain measurement using SAW sensors has not been reported previously. Wireless measurement of strains overcomes traditional barriers to monitoring where the practicalities of wiring to strain gauges are a significant impediment to the application of monitoring on moving tools.

Strain measurement on the tooth provided significant strain levels from both the wired and wireless SAW strain sensors. It is conceivable that when transferring to a full broaching machine, issues of stiffness would be resolved There are likely to be additional sources of noise that may have an impact on signal integrity in the wireless SAW strain sensors. Through appropriate miniaturisation and suitable integration of antenna, wireless strain measurement may be a solution for test lab setup on traditional and high end broaching tool geometries such as the fir-tree shape.

Strain measurement on the broaching tool structure demonstrated the versatility of the resistive strain gauge in identifying the principal strain and strain orientations during loading and cutting. The wireless SAW strain sensor demonstrated that strain was measurable. However the low strain levels, issues with the sensitivity of the wireless SAW strain sensor to the principal strain directions and noise content in the interrogation system are challenges that require further work. Multi-axis strain measurement using wireless SAW sensors is the subject of ongoing research.

Acknowledgements

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