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An Integrated Telemetric Thermocouple Sensor for Process Monitoring of CFRP Milling Operations

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Abstract

A wireless temperature measurement system was developed and integrated into a cutting tool holder via a thermocouple embedded within the cutting tool. The primary purpose of such an embedded thermal measurement sensor/system is for online process monitoring of machining processes within which thermal damage poses a significant threat both for the environment and productivity alike – as is the case with the machining of carbon fibre reinforced polymer (CFRP) components. A full system calibration was performed on the device. Response times were investigated and thermal errors, in the form of damping and lag, were identified. Experimental temperature results are presented which demonstrate the performance of the integrated wireless telemetry sensor during the edge trimming of CFRP composite materials. Thermocouple positioning relative to heat source effect was among the statistical factors investigated during machining experiments. Initial results into the thermal response of the sensor were obtained and a statistical package was used to determine the presence of significant main effects and interactions between a number of tested factors. The potential application of the embedded wireless temperature measurement sensor for online process monitoring in CFRP machining is demonstrated and recommendations are made for future advancements in such sensor technology.

Keywords: Sensor ; Temperature ; In-process measurement

1. Introduction

The concept of a sensor designed to measure some response/behaviour of a machining process is a fundamental part of process monitoring and control.

Nomenclature

dQ	Rate of change of heat flux (W)
α	Thermal conductivity of the sensor-object boundary (W m^{-1} K^{-1})
T_B	Temperature of bulk object (K)
T_S	Sensor temperature (K)
m	Sensor mass (kg)
c	Specific heat (J kg^{-1} K^{-1})
τ_T	Time constant (**m.c.** α^{-1}) (s)
ΔT	Temperature difference (T_B - T_S) (K)
t	Time vector for sensor exposure to heat (s)

This is more clearly understood by way of the surmisal of the sequence of events in a process monitoring and control system outlined by Teti *et al.* *[1]*: Process variables → **sensorial perception** → data processing and feature extraction → cognitive decision making → action.

Using the traditional categories of direct and indirect measurement approaches to quantify process responses, a key physical process property which contributes

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strongly to the use of indirect measurements for process control is temperature. Temperature has long been correlated to destructive and costly production facets of traditional metal machining, such as tool wear. [2]

Additionally, with plastic and composite machining becoming ubiquitous particularly in the aerospace industry, thermal damage of the workpiece has become another such facet. [3]

While various sensors have been developed to monitor machining process temperature, intermittent, high speed composite machining processes involving complex geometries in rotation remain without a robust and accurate temperature process monitoring tool. This lack of sensor availability is also due to the requirement that such a sensor must not significantly change the process conditions. [4]

1.1. Damage caused during CFRP milling

In the machining of CFRP composites, a secondary process in CFRP component manufacture, a principal process quality criterion is to ensure that the high value-added component surface remains damage free post-machining. The most common machining processes performed on CFRP components are drilling and milling operations [5].

Thermal degradation is known to damage the already high-value added moulded CFRP component [6]. For a typical epoxy-based CFRP material, this critical temperature is approximately 180°C - 270°C [6].

As well as the thermal effect of the milling process on the CFRP workpiece, the abrasive, brittle nature of chip formation during this process is also known to cause significant tool wear [7]. This has lead to novel tool designs and a move from carbide to PCD cutting tools to reduce long-term costs associated with the production of CFRP components.

The brittle nature of chip formation in CFRP intermittent cutting results in only a small proportion of the heat dissipation via chips during the machining process [7], presenting the need for process monitoring with a thermal sensor.

1.2. State-of-the-art in milling temperature measurement

Of critical importance to the design of any sensor is the location at which the measurement is taken and how this relates to the process response under study, i.e. tool wear or surface integrity. This is particularly true for the case of temperature measurement. During a machining process, the tool, workpiece and chip thermal properties dictate how heat is transferred through the cutting system [8]. Thus, by determining the temperature associated with one of these constituents, the heat flux associated with the cutting mechanism can be established. Therefore, the determination of temperature at the cutting tool, workpiece or chip could hypothetically be used to infer the process temperature.

Methods such as the inverse heat transfer technique [9] have been applied in machining applications to estimate the temperature at the cutting interface based on measurements taken from sensors within the cutting tool [10].

In an extensive temperature measurement in machining review, Davies *et al.* [11] indicate that the use of thermocouples for temperature measurement in material removal processes represents the state of the art. Most recently, cutting tools with embedded thermocouples as sensors were used by Brinksmeier *et al.* [12] to determine tool temperatures during conservative CFRP drilling experiments, limited to a static tool scenario. Werschmoeller *et al.* [13] employed a micro thin film thermocouple to determine the temperature from an embedded position in the tool. The authors recorded response times of 150 ns using short pulse duration shots from a Nd:YAG laser.

Ueda *et al.* [14] applied the two-colour pyrometry technique to an end-milling process using a non-contact coupler to measure the temperature of the underside of a rotating CBN tool rake face. However, no mention is made by the authors of the effect of CBN tip material thickness upon the temperature data obtained.

2. Integrated telemetric temperature (ITT) sensor characterisation

As a result of a review of previous studies, the design of a sensor which incorporates the embedded thermocouple, in conjunction with the transmission of wireless signals, was developed by ACTARUS. This design incorporates all transmission modules on the tool and tool holder section of the rotating system.

2.1. Wireless temperature via inductance

The components of the wireless telemetry system which enable the transmission of voltage, produced by way of the Seebeck effect, from a spindle and tool rotating at speeds of up to 200 mm/min are outlined in figure 1. The principle components of this sensor design are; 1) Signal input and conditioning; 2) Transmission module; 3) Receiver module; 4) Processing module. In this system of components, the signal received from the input thermocouple sensor embedded in the tool is connected to a thermocouple module which allows for cold junction referencing, amplification and filtering of the analogue voltage signal. The signal is then transferred to a transmission (ADC) module which converts the analogue signal to a digital pulse code modulated (PCM) representative signal.

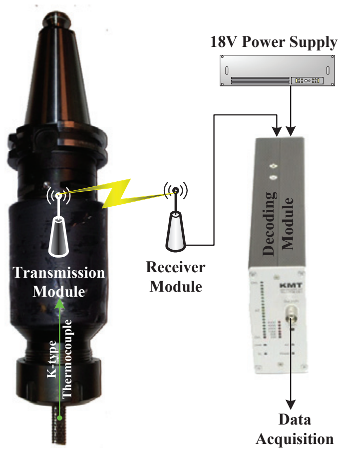

Fig. 1. Telemetry system and components required to deliver thermocouple signals from the cutting tool to the PC.

This signal is transferred to an induction coil which transmits the voltage signal to the stator. Power is supplied inductively to the transmission modules from the stator.

2.2. ITT sensor installation

The core of the temperature measuring sensor is a k-type thermocouple (TC) embedded within an 8 mm diameter solid carbide cutting tool. The diameter of the thermocouple used is 0.2 mm and the nominal rated response is approximately 20 ms. The TC is embedded as shown in figure 2, with a precise 0.6 mm groove bored into the cutting tool for TC insertion up to a distance of approximately 0.5 mm away from the cutting edge. A customized toolholder allowed access for the TC and accommodated the signal conditioning and transmission module and components.

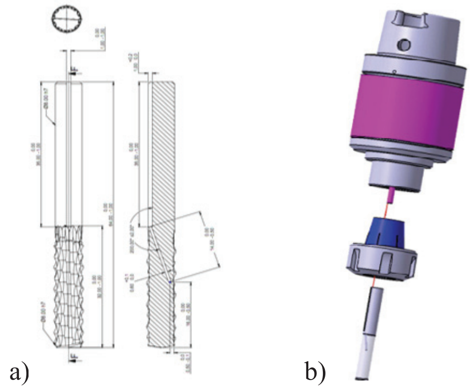

Fig. 2. (a) Thermocouple location within the solid carbide cutting tool. (b) The sensor route from thermocouple to signal transmission.

2.3. Static response and system calibration

To begin the system calibration, the ITT system was connected to an NI DAQ system with LabVIEW SignalExpress software. The system calibration was performed using a highly accurate temperature calibration dry block having a certified uncertainty of 0.02°C over the range of 0°C < T < 600°C.

The sensitivity of the ITT sensor system under steady state was approximately 6.59µV/°C for temperatures in the range of 20°C to 175°C. This is in comparison to typical sensitivity values for bare wire k-type thermocouples of approximately 41 µV/°C.

This discrepancy is likely a result of the additional carbide tool mass associated with the ITT sensor system, adding thermal mass and therefore thermal inertia to the system.

2.4. Newton's law of heating

For a dynamic conductive boundary between a bulk object transferring thermal energy to a sensor, combining Newton's Law of Heating and the specific heat equation produces the first order differential equation:

$$dQ = \alpha(T_B - T_S)dt = m.c.dt \qquad (1)$$

Where *m,* the sensor's mass and, *c,* the sensor's specific heat properties are assumed as average values for the sensor. Hence, the heat absorbed by the sensor can be expressed mathematically as the solution to equation 1 as:

$$T_S = T_B - \Delta T\left(e^{-t/\tau_T}\right) \qquad (2)$$

In equation 2, the time constant, τ_T, for this sensor, based on a step input at $t = 0$ for a first order system, was calculated as 63.2% of ΔT, using the initial gradient between T_B and T_S.

Assumptions which must be enforced for equation 2 to hold are:

- Thermal resistance between the sensor and the environment is infinitely large.
- The object's temperature does not change after the sensor is attached (infinite heat source).

Both of these assumptions are reasonable for the setup associated with the system calibration.

The goal of performing a dynamic calibration on the system was to determine an experimental value for the time constant and hence compare the sensors behaviour to theory. Using the experimental setup from the static system calibration described previously, the ITT signal responses were scrutinised for a range of setpoint, T_B.

2.5. Dynamic response testing and calibration

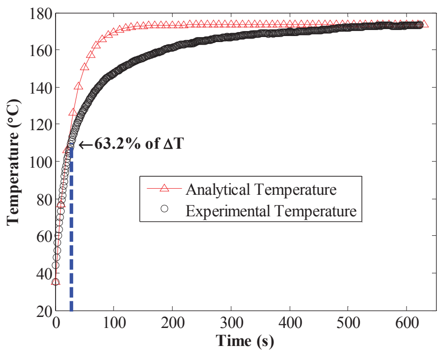

Fig. 3. Comparison of analytical and experimental response of ITT sensor for a bulk temperature, T_B, of 175°C.

Comparing the response of the ITT sensor during these tests with theory indicates an under-performance by the sensor in experiments in achieving bulk temperature, as indicated in figure 3.

The difference in dynamic response of experimental and analytical results is due to the additional thermal resistance added by the tool material, which separates the TC head from the infinite heat source resulting in a time constant in the range 25.2 sec < τ_T < 27.9 sec for a temperature range of 20°C < T_B < 175°C.

2.6. Dynamic response with localised heating and tool rotation

To determine the effect of changes in temperature at the cutting interface using localised heating on the ITT sensor an alternative dynamic calibration experiment was used.

The alternative experiment was set up using a controlled heat source applied via a forced convection heated jet. The surface temperature was monitored by a pyrometer with a spot size of 0.6mm, calibrated to the surface of the cutting tool with an emissivity of 0.32.

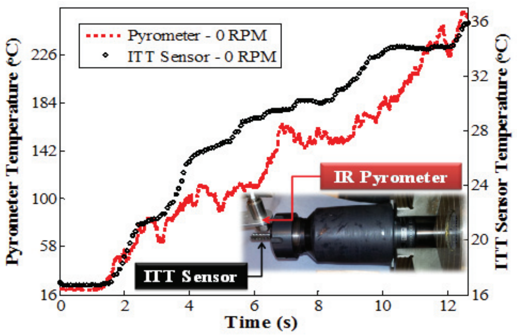

Fig. 4. Comparative results of embedded ITT sensor and tool surface sensor (pyrometer) for the case with no tool rotation.

The results, shown in figure 4, describe a discrepancy due to thermal inertia effects between the temperature measured by the ITT sensor and that recorded by the pyrometer. The former senses approximately 14-24% of the surface temperature at the upper range of temperatures. Figure 4 illustrates the pyrometer's ability to detect more rapid changes in the surface temperature, caused by changes to the dynamic of the experimental environment.

3. Milling investigations

3.1. Experimental setup

Milling tests were performed using a HUCRO VM2 3-axis vertical milling machine. The edge trimming process was performed over a distance of 150 mm for each cutting test to prevent any significant reductions in tool condition throughout the tests and to optimise the workpiece material usage. The setup for this experiment is shown in figure 5, which indicates the ITT on-tool system and separate stator connected a distance of 20mm apart.

The data acquisition system (DAQ) used for this experiment incorporated an NI PXI-4472B 16-channel acquisition module housed in a PXI-1033 chassis interfaced to a PCIe Netbook. Custom-built LabVIEW software was used to acquire the temperature and force signals and store data.

A Kistler workpiece dynamometer was synchronized via the DAQ system clock with the ITT sensor system in order to detect the onset of the cutting process. This was done in order to determine the response of the ITT sensor during the cutting process.

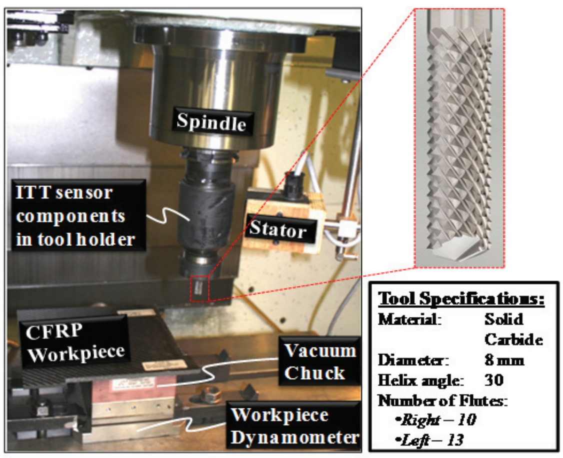

Fig. 5. Setup for edge trimming experiments using ITT sensor.

A solid carbide milling rougher of 8mm diameter made up the cutting component of the ITT system. The tool was examined using a Dino-Lite 5 megapixel microscope pre- and post-testing to determine tool condition. The workpiece was a quasi-isotropic carbon fibre-epoxy polymer composite sheet manufactured from ACG Ltd. prepregs oriented, laid up by hand, and brought through a vacuum bag curing process.

The configuration of plies in this material is represented by $[0°/90°]_m[45°/-45°/-45°/45°]_n[90°/0°]_m$, where n and m represent the proportion of prepreg plies of areal density 800 gsm and 100gsm respectively. This configuration generates a quasi-isotropic structure symmetric about its centre.

3.2. Experimental design

Table 1. Factors and 2-level settings used during screening experiment

Factor	Stat. Abbr.	Units	Low	High
Cutting speed	A	m/s	60	201
Feed rate	B	mm/min	375	1275
Depth of cut	C	mm	1	3.4
Workpiece thickness	D	mm	1	5
Workpiece fibre orientation	E		0/90/ -45/45	90/0 /45/-45
Vertical cutting position	F		Tool Tip	@ ITT sensor
Workpiece overhang	G	mm	5	17

A heuristic approach was taken to identify those factors which could potentially have the most influence on the process temperature. These were identified as cutting speed (CS), feed rate (FR), depth of cut (DOC), workpiece thickness (WPT), workpiece fibre orientations (FO), vertical cutting position/strategy (VCS) and workpiece overhang (O). Table 1 displays the 2-level settings selected for each of the factors.

A fractional factorial experimental design was chosen to give an initial insight into any potentially significant parameters associated with the process. This screening test was limited to 8 runs per replicate using a 2^{7-4} factorial design. The experiment was randomized based on 3 reps for each of the 8 design points for repeatability purposes. The factor levels applied for each run are outlined in table 1.

3.3. Preliminary results for temperature monitoring of CFRP milling

The measurement data for a single repetition of the experiment for the ITT sensor is illustrated in figure 6.

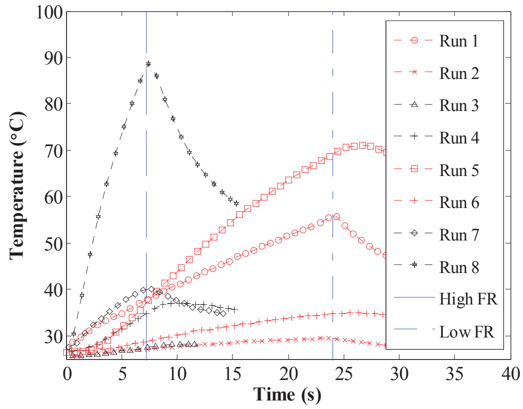

Fig. 6. Temperature results for the screening tests using ITT sensor in CFRP milling experiments.

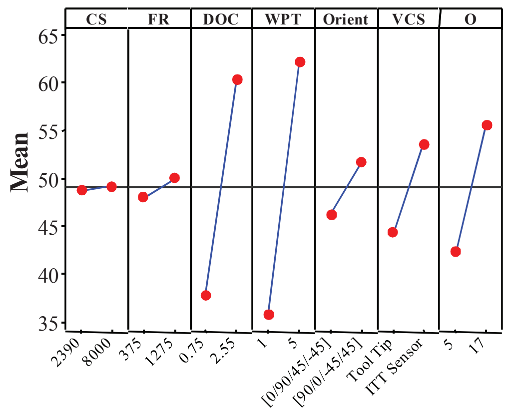

Fig. 7. Main effects plot resulting from the CFRP edge trimming screening test.

A main effects plot, generated from the temperature results of the factorial analysis is displayed in figure 7. This plot indicates that for the temperatures measured by the tool, factors C (DOC) and D (WPT) produced the largest main effect plot.

From the interaction plots of figure 8, there is evidence of strong 2-level interactions associated with the main effects from figure 7. The link between the strongest interactions and the main effects are displayed in table 2, where such interactions are represented in bold red text.

Due to the number of significant interaction effects, the experimental factors must be considered together, if the nature of the cutting system is to be understood.

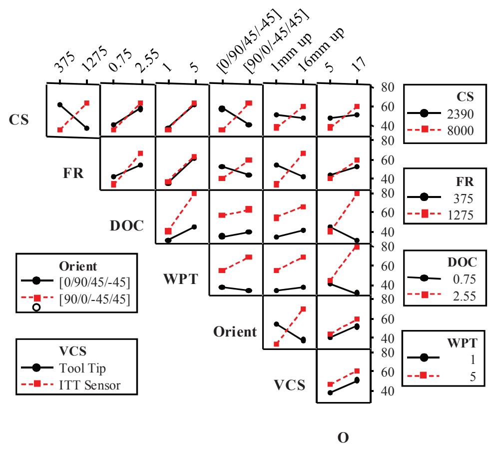

Fig. 8. Interaction plots resulting from the CFRP edge trimming screening test.

Table 2. Key 2-level interactions confounded with main effects (highlighted in red)

Factors			
CS	→ A+BD+CE+FG	FO	→ E+AC+DF+BG
FR	→ B+AD+CF+EG	VCS	→ F+BC+DE+AG
DOC	→ C+AE+BF+DG	O	→ G+CD+BE+AF
WPT	→ D+AB+EF+CG		

4. Conclusions

This work points out the strong potential for the use of wireless telemetric systems within rotational cutting tool temperature measurement applications. Further findings from this work include:

- Calibrated temperature data was acquired via a wireless integrated tool-thermocouple sensor during a milling process.
- The cutting tool mass introduces time delays, resulting in reduced sensitivity of the ITT sensor.
- Workpiece thickness and depth of cut produced the most considerable impact on milling process temperatures, with vertical cutting strategy showing a smaller effect and 2-level interactions causing an aliasing effect.
- Limitations such as lag and damping exist for the current ITT sensor will be addressed in future works.

5. Future works

This work initializes the development of a fully characterised in-tool sensor. Future works should include:

- A method should be developed to relate the lagging ITT sensor temperature to tool surface temperature.
- Development of a more responsive sensor by either reducing tool thermal inertia or repositioning sensor.
- Characterisation of the ITT sensor to include tool rotational and longitudinal effects on sensor response.

6. Acknowledgements

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References

[1] Teti R, Jemielniak K, O'Donnell G and Dornfeld D. Advanced monitoring of machining operations. CIRP Annals - Manufacturing Technology. 2010;2:717-39

[2] Taylor J. The tool wear-time relationship in metal cutting. `International Journal of Machine Tool Design and Research. 1962;2:119-52

[3] Rawat S and Attia H. Characterization of the dry high speed drilling process of woven composites using Machinability Maps approach. CIRP Annals - Manufacturing Technology. 2009;1:105-8

[4] Klocke F, Gierlings S, Brockmann M and Veselovac D. Influence of Temperature on Surface Integrity for Typical Machining Processes in Aero Engine Manufacture. Procedia Engineering. 2011;0:203-8

[5] Teti R. Machining of Composite Materials. CIRP Annals - Manufacturing Technology. 2002;2:611-34

[6] Chatterjee A. Thermal Degradation Analysis of Thermoset Resins. Journal ofApplied Polymer Science. 2009;1417–25

[7] Sasahara H, Ogawa T and Yashiro T. Cutting Temperature Measurement on Milling Process of CFRP. Proceedings of the 4th CIRP International Conference on High Performance Cutting. 2010;255-9

[8] Müller-Hummel P and Lahres M. Quantitative measurement of temperatures on diamond-coated tools during machining. Diamond and Related Materials. 1995;10:1216-21

[9] Ozisik MN and Orlande HRB. Inverse Heat Transfer: Fundamentals and Applications. London: Taylor & Francis; 2000

[10] Rech J, Battaglia JL and Moisan A. Thermal influence of cutting tool coatings. Journal of Materials Processing Technology. 2005;1:119-24

[11] Davies MA, Ueda T, M'Saoubi R, Mullany B and Cooke AL. On The Measurement of Temperature in Material Removal Processes. CIRP Annals - Manufacturing Technology. 2007;2:581-604

[12] Brinksmeier E, Fangmann S and Rentsch R. Drilling of composites and resulting surface integrity. CIRP Annals - Manufacturing Technology. 2011;1:57-60

[13] Werschmoeller D and Li X. Measurement of tool internal temperatures in the tool-chip contact region by embedded micro thin film thermocouples. Journal of Manufacturing Processes. 2011;2:147-52

[14] Ueda T, Sato M, Hosokawa A and Ozawa M. Development of infrared radiation pyrometer with optical fibers—Two-color pyrometer with non-contact fiber coupler. CIRP Annals - Manufacturing Technology. 2008;1:69-72