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Semiconductor strain gauges as potential replacement to metal foil for cutting force measurement in machining process

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KEYWORDS

Strain gauge
Dynamometer
Cutting force
Machining
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ABSTRACT

This study presents a comparison of the cutting force measurement performance using two types of strain gauges, namely metal foil and semiconductor, installed into a low-cost dynamometer. Static measurements were first conducted to study signal behavior prior to cutting. Then, turning operations were set for cutting AISI 4340 alloy steel using carbide tools. The results revealed that semiconductor strain gauges were up to 20 times more sensitive than metal foil strain gauges in three cutting force axes. Nevertheless, span drift error was very much present especially after a 60 second period. The machining study conducted showed that semiconductor strain gauges initially yielded lower resultant forces before gradually increasing to a similar trend as the metal foil strain gauges. This study highlights the potential of semiconductor strain gauges to be used for cutting force measurements in machining due to its greater sensitivity and accuracy. However, for prolonged and continuous machining operations, especially for industrial applications, metal foil strain gauges are still favorable due to their measurement consistency and stability.

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1.0 INTRODUCTION

Machining is an important manufacturing processes used for producing different kinds of metallic components and parts in industrial sectors such as automotive, aerospace and construction. It is commonly applied as a secondary process after primary metal forming to get the final form and dimensions of components (Kuntoglu et al., 2021). Some delicate parts may require ultraprecision machining down to the lowest possible scale (Trent & Wright, 2000). Good final surface quality is therefore essential to produce precise geometry and standard functional performance of components (Ambrosy et al., 2014). Machined surfaces are highly affected by cutting tool condition. Excessive stresses and thermal softening within the tool edge, due to large friction during machining, may cause the tool to deteriorate, leading to loss of cutting edge, hence, affecting the parts dimensions and surface finish quality (Ghani et al., 2010). Approximately 20% of machine downtime reported has been due to tool failure, in which tool replacement may account for up to 12% of total production cost (Rizal et al., 2013).

In order to improve quality of the machined parts and reduce production cost and time, tool condition monitoring (TCM) has been introduced. It enables tool wear status, chatter, tool breakage, and collision to be monitored and has been extensively explored by researchers since the 1980s (Byrne et al., 1995). Instead of directly measuring tool wear, which is difficult due to continuous contact between the tool and the machined parts, as well as with the presence of coolant fluids (Rizal et al., 2017), online monitoring via sensor signals can be used to detect for measurable machining signals. These signals correlate well with changes in tool wear and can be used to determine cutting tool condition (Kuntoglu et al., 2021; Lauro et al., 2014; Mutalib et al., 2020).

One of the most important machining signals employed in tool condition monitoring is cutting force signal (Rizal et al., 2013; Trent & Wright, 2000). It is generated by the cutting tool as it cuts and shears the workpiece (Rizal et al., 2014). As machining progresses, sharpness of the cutting tool reduces due to wear. This leads to a gradual increase in contact area and increased difficulty when removing the chip under similar cutting conditions which leads to a higher cutting force requirement (Kuntoglu et al., 2021). Specifically in turning processes used for machining cylindrical workpieces, cutting force signals provide higher sensitivity against tool wear as compared to other measurands such as vibrations and acoustic emissions (Byrne et al., 1995). This signal, therefore, has become the most common variable for tool wear indication, cutting process optimization, and for fundamental study of machining performance.

Cutting force is commonly measured by using sensor devices such as strain gauges. It is a type of sensor that experiences a change in resistance when stretched or strained under applied loads (Moris & Langari, 2012). Since its invention in 1938, strain gauges have been widely used in stress tests and force measurements of various components in industries (Zhao et al., 2020). In machining, this sensor is commonly applied as part of of a dynamometer mounted to machining tools to measure force signals (Rizal et al., 2018). As the world moves towards Industrial Revolution 4.0, high-speeds and high-precision has become an outstanding feature in the machining industry. This requires faster cutting speeds and smaller cutting parameters, resulting in reduced and fast changing cutting forces (You Zhao et al., 2016). Thus, sensors should have high sensitivity to measure these forces with accuracy, apart from being low cost, compatible, and reliable when considering their respective industrial application.

Metal foil is a widely known strain gauge type used in tool condition monitoring due to its accuracy and stability, while the semiconductor type has only recently been gaining attention due to its higher sensitivity and superior gauge factor (Moris & Langari, 2012; Zhao et al., 2020).

According to Hitechsensors (2020), the decision for using semiconductor strain gauges over more traditional foil gauges often come down to the need for greater safety. Semiconductor gauges typically have small, simple, straight strips that can produce up to 50 times more electrical output relative to the strain experienced in metal foil gauges (DFE, 2021). Thus, less force is required to produce a measurable output signal allowing for a more robust dynamometer design and better protection from overload. In addition, the larger signal output allows for measurements of very low stresses without signal loss as electrical noise (DFE, 2021). This is especially helpful in high precision machining whereby very small cutting forces are produced. Nevertheless, metal foil strain gauges, with its widespread availability and low fabrication cost, is still the popular choice currently in the market (Hitechsensors, 2020). Semiconductor strain gauges are also relatively new in tool condition monitoring and more studies are required to prove its accuracy and consistency for further application in machining.

In this present study, measurement performance of cutting forces during machining of AISI 4340 alloy steel using carbide tools was done utilizing a low cost, in-house dynamometer. Two types of strain gauge materials, namely semiconductor and metal foil, were used as sensors for the dynamometer. The study data was then related to tool wear trend. The focus for this study is to analyse the feasibility of both sensors in terms of sensitivity, accuracy, and consistency, as well as identifying the most suitable sensor to be implemented into the dynamometer for cutting force measurements and tool condition monitoring in machining operations.

2.0 EXPERIMENTAL PROCEDURE

Table 1 shows the properties of the strain gauge sensors based on the metal foil and semiconductor used in the study. The sensors were installed into the dynamometer for cutting force measurements during machining.

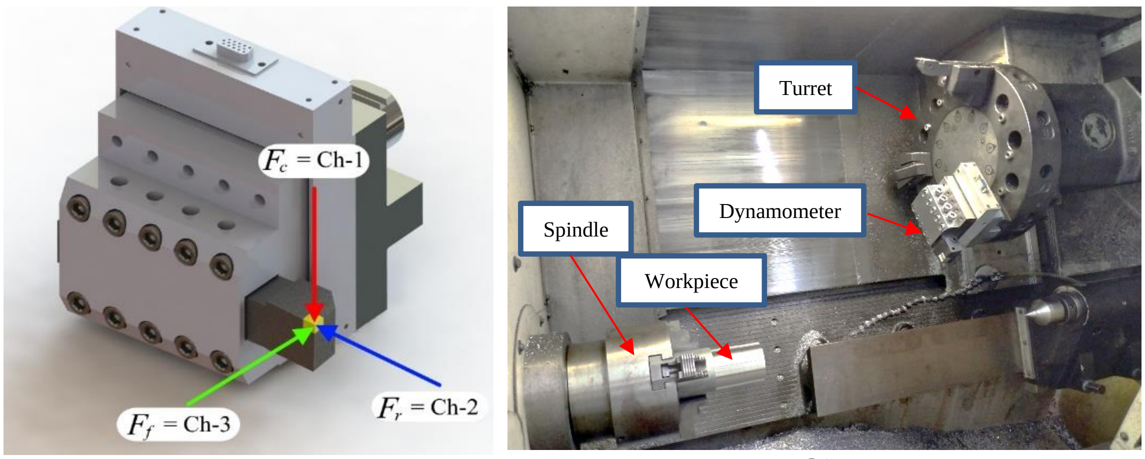
Table 1: Properties of strain gauge sensors.

Type	Gauge Factor	Nominal Resistance	Tolerance	Brand
Metal foil	2.14	350 ohms	+/- 0.3%	Omega
Semiconductor	150.00	350 ohms	+/- 5.0%	Utop

This experiment was carried out on a CNC lathe machine, model Colchestor Tornado T4, set up as shown in Figure 1. The overall system used for this study is called Neo-MoMac™ (Rizal et al., 2013) which consists of:

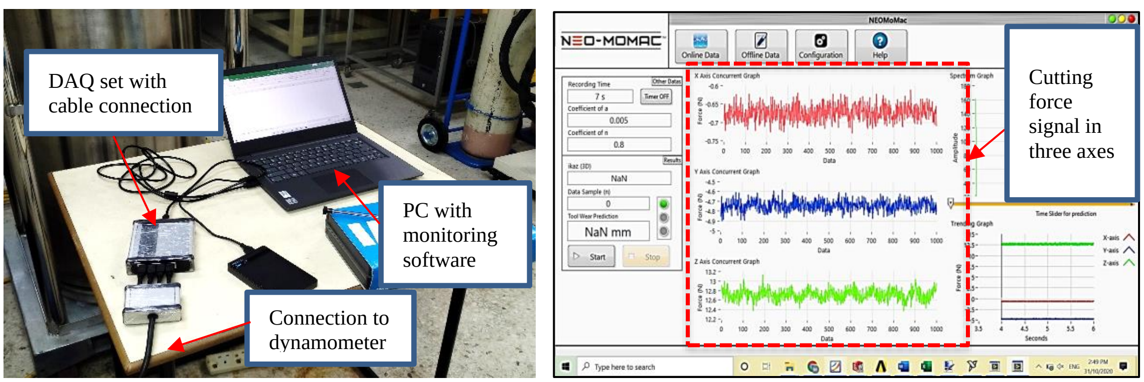
(a) Dynamometer: Strain gauge-based sensor, either of metal foil or semiconductor type.
(b) Data acquisition system (DAQ): Used for signal conditioning and processing.
(c) User Interface Software: Developed in-house by UKM researchers for data monitoring.

The dynamometer was first mounted on the tool holder of the turret, and the full set up is shown in Figure 1 (a) and (b). Cutting force signals were measured in three directions: Cutting force (Fc) Feed force (Ff), and Radial force (Fr). The workpiece used was AISI 4340, a heat-treatable low-alloy medium carbon steel that is widely used in applications that require high strength and wear resistance such as crankshafts, landing gear, and high tensile screws (Ahmad et al., 2021). Meanwhile, the cutting tool used was of carbide material with code CNMG120408-MF4.



(a) (b)

Figure 1: a) Dynamometer and tool holder assembly; b) Machining test setup to evaluate the performance of the dynamometer.



(a) (b)

Figure 2: (a) Connection setup between the DAQ and computer (b) Force signals from the dynamometer are displayed on the computer screen.

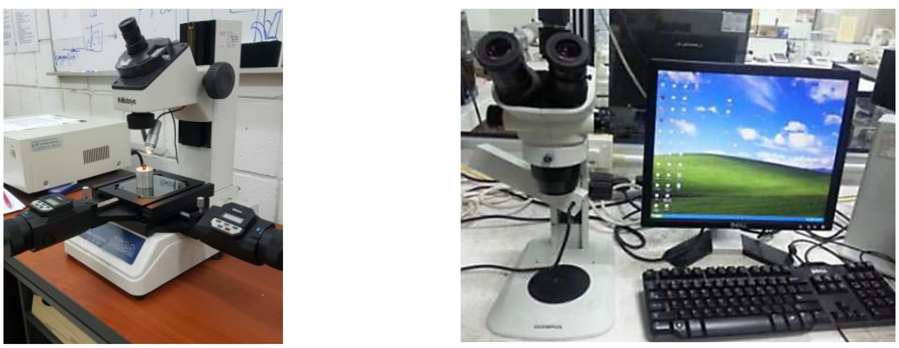
The signals obtained by the dynamometer were transmitted for data acquisition via cable connection to the computer equipped with Neo-MoMac™ monitoring software, as shown in Figure 2 (a) and (b). In this study, the experiment was conducted in two stages. The first stage included a static test to study signal behavior in terms of stability and consistency prior to cutting. Once calibration was done, the dynamometer was activated using the software and left to self-run without involving any cutting processes for a period of five minutes. The signals captured for both strain gauge types were saved. After a two-week interval, the test was repeated to study output consistency.

The second stage involved a machining process (turning operation). Table 2 shows the cutting parameters for this experiment. High cutting parameters were intentionally used to accelerate tool wear progression and to obtain higher cutting forces.

Table 2: Cutting parameters.

Parameter	Description
Cutting speed	200 m/min
Feed rate	0.3 mm/rev
Depth of cut	1 mm

Neo-MoMac™ software was used to monitor and save the cutting force signals captured from the dynamometer. After each run, the tools were detached from the machine and their wear progression was measured using a microscope (Mitutoyo TM-500), as shown in Figure 3 (a). It was equipped with a micrometer with a resolution of up to 1μm. The experiment continued until wear measurements reached the standard average tool flank wear limit (VB_{avg}) of 0.3mm (*ISO 3685:1993 Tool-Life Testing with Single-Point Turning Tools*, 1993). Once the tool reached wear limit, its wear image was then captured and marked using an optical microscope (Olympus) with Vis software as shown in Figure 3 (b).



(a) (b)

Figure 3: (a) Mitutoyo TM-500 microscope (b) Olympus optical microscope with Vis software.

3.0 RESULTS AND DISCUSSION

3.1 Static Test

Figure 4 shows the overall cutting force signal results using the dynamometer based on metal foil strain gauges. The signals were constant at around 0N throughout the testing period. This is a good indication of the dynamometer's stability and accuracy since no cutting force was supposed to be detected under static conditions. However, the signal range and peak amplitude was quite large reaching up to 20N. As such, dynamometers based on metal foil strain gauges may not be suitable for machining operations which require high precision as the forces generated are typically lower and will be difficult to monitor (Sousa et al., 2020).

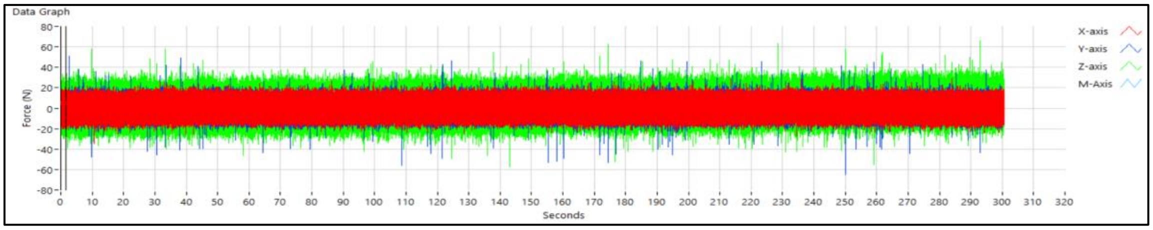


Figure 4: Static cutting force signals using dynamometer based on metal foil strain gauge.

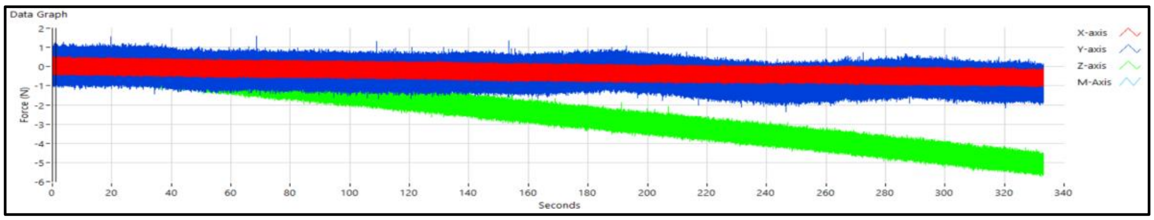


Figure 5: Static cutting force signals using dynamometer based on semiconductor strain gauge.

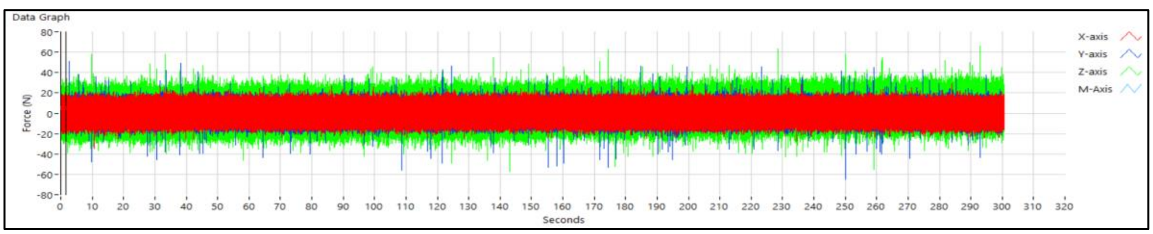


Figure 6: Static cutting force signals using dynamometer based on metal foil strain gauge (two-week interval).

Figure 5 shows the overall cutting force signal results using the dynamometer based on the semiconductor strain gauges. Despite starting at 0N, the signals were found to be unstable and gradually changed throughout the measured period. This phenomenon can be related to span drift error, which is an error caused by gradual shifts in measured values over time. This error can be due to several factors which include preloading, incidental contact, temperature changes, vibrations, electromagnetic field, wear and tear, and debris accumulation (DFE, 2021). This error causes a proportional increase or decrease in measured values away from calibrated values. Nevertheless, the signals were highly sensitive with a peak amplitude of only 1N during a stable period in the first 60 seconds, as expected of the semiconductor with a higher gauge factor (Moris & Langari, 2012; Zhao et al., 2020).

Figure 6 and Figure 7 show the overall cutting force signal results using the dynamometer based on the metal foil and semiconductor strain gauges respectively after a two-week interval. No changes were made to the dynamometer prior to testing including calibration.

As shown from the previous figures, the dynamometer based on metal foil (Figure 6) produces constant cutting force signals similar to the previous test done two weeks earlier. This indicates consistency for this dynamometer despite a longer holding period without any calibration. Meanwhile, the dynamometer based on semiconductor (Figure 7) continued to show span drift with its results trending differently from its previous test, showing inconsistency. Nevertheless, the signals from the semiconductor strain gauges showed stable measurements for the first 60 seconds with a peak amplitude of only 1 N, significantly more sensitive than the metal foil strain gauges at 20N peak amplitude.

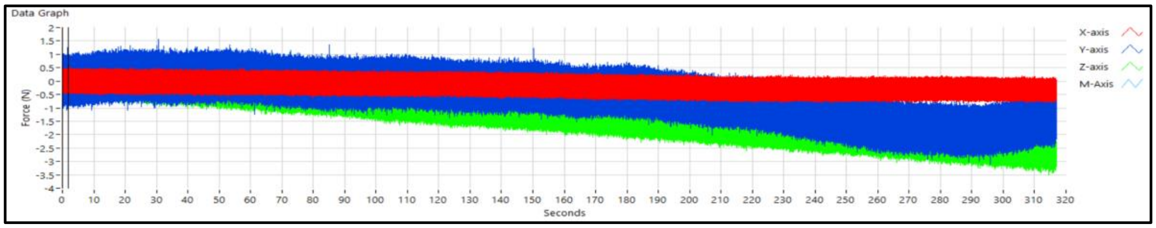


Figure 7: Static cutting force signals using dynamometer based on semiconductor strain gauge (two-week interval).

3.2 Machining Test

Figure 8 shows the tool average flank wear (VB_{avg}) against cutting time (t) using the dynamometer based on semiconductor and metal foil strain gauges respectively.

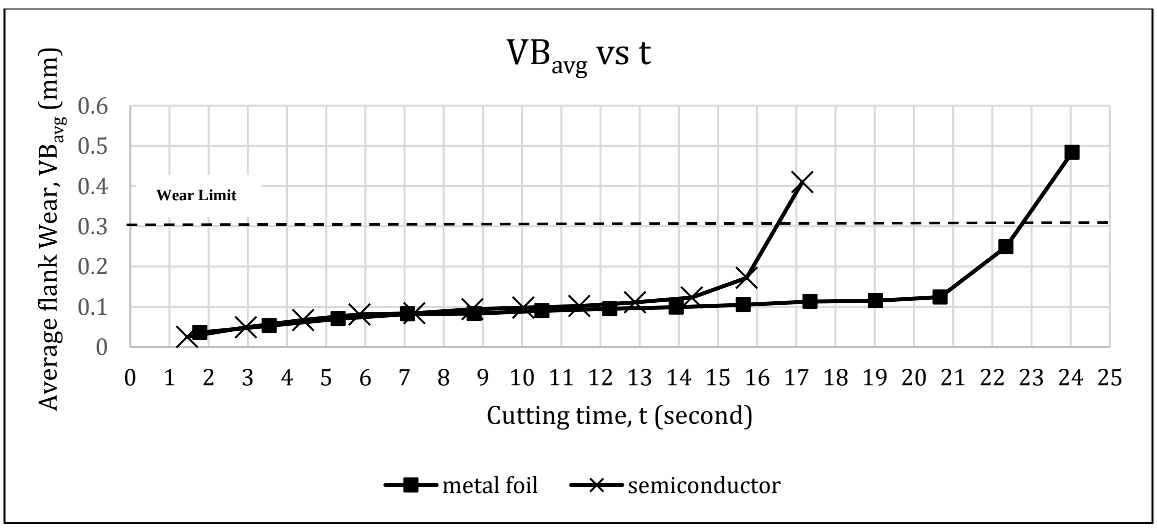
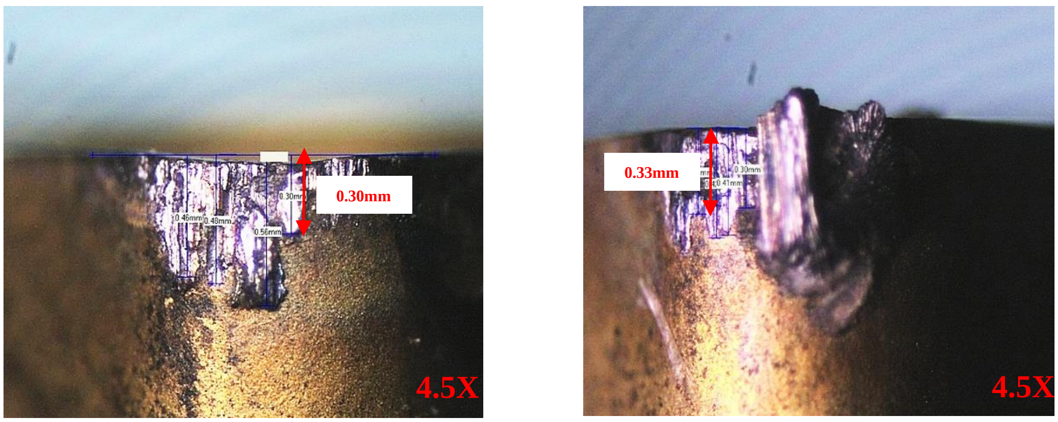


Figure 8: Comparison of tool average flank wear against cutting time using dynamometer based on semiconductor and metal foil strain gauges. Wear limit is at 0.3 mm as indicated by the dashed line.

Based on Figure 8, both cases show increased wear trend as time progressed. However, the metal foil strain gauge took a longer time to reach wear limit at 22.5 seconds as compared to the semiconductor strain gauge which took 16.5 seconds despite having the same cutting parameters. The wear rate for both of these cases started with a similar trend in the beginning and started to differ at around the 13-second mark. In order to understand this phenomenon in detail, microscopic observation on the surface of the tool flank wear was carried out for both cases.

Based on Figure 9, both cases reached the wear limit of 0.3 mm. However, there is a difference in wear behavior of the tools. As can be seen in Figure 9 (b), there exists a built up edge (BUE) formation on the flank surface. High feed rates and cutting speeds give rise to a fast temperature increment that result in material adhesion to the tool edge due to thermo-mechanical effects (Butt et al., 2021; Yezika et al., 2019). The BUE triggered the tool to wear faster. This is especially true for softer metals with a low melting point such as aluminium (AISI 4340). Nevertheless, the BUE formation is unstable during machining and may come in a variety of sizes as can be seen from Figure 9 (a) with smaller BUE. This results in the ability of longer wear limit for the metal foil case as compared to the semiconductor case.



(a) (b)

Figure 9: Comparison of microscopic observations of tool average flank wear at 4.5X magnification for (a) dynamometer based on metal foil strain gauges and (b) dynamometer based on semiconductor strain gauges.

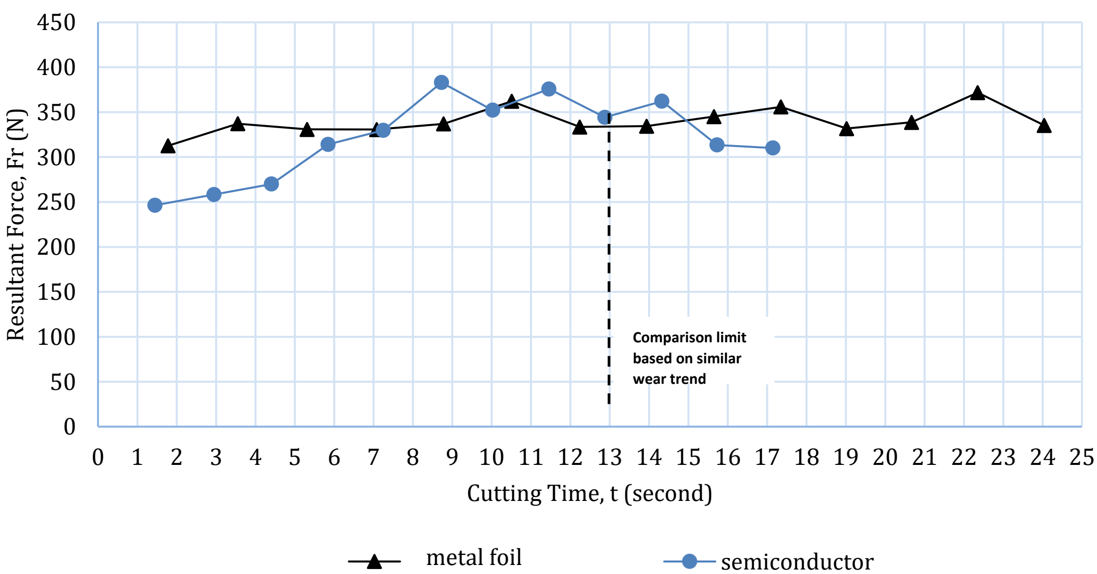


Figure 10: Comparison of resultant cutting forces against cutting time using a dynamometer based on metal foil and semiconductor strain gauges.

Figure 10 shows the resultant cutting forces obtained from a combination of Cutting force (Fc) and Feed force (Ff) as the active forces in the turning process. For the purpose of comparison, the cutting time was limited to 13 seconds following similar wear trends as seen in Figure 8. In the first 5 seconds, the semiconductor strain gauge produced a lower resultant force as compared to the metal foil strain gauge. This trend can be explained due to the higher sensitivity of the semiconductor against the metal foil as discovered through the static test, allowing it to capture more refined force signals and lowering the initial resultant force. However, continued tool wear lead to a higher cutting force requirement (Kuntoglu et al., 2021). The resultant force using the semiconductor increased to a similar value as the metal foil at the 13-second mark in which the comparison limit was reached. The force fluctuations throughout the cutting period is believed to have been due to the presence of BUE or debris that prevented the machined surface from having constant contact with the tools, hence,affecting cutting force measurements.

CONCLUSION

In this study, a comparison of cutting force measurement performance using two types of strain gauges, namely metal foil and semiconductor which were embedded into a low cost, in-house dynamometer, was conducted. The following can be concluded from the study:

(a) Through the static test, the dynamometer based on the semiconductor strain gauges was found to provide better sensitivity up to 20 times more as compared to the metal foil strain gauges. However, the presence of span drift error hinders its used in prolonged operations, specifically, more than 60 seconds, due to inconsistency.

(b) Despite similar cutting parameters, wear progression between both cases differed due to BUE formation during machining after some time. Under the time comparison limit, the semiconductor strain gauges were found to yield lower resultant forces initially, before gradually increasing to a similar trend as the metal foil, indicating better sensitivity and accuracy. Only slight changes in resultant forces can be observed between the two materials as time and tool wear progressed.

(c) In terms of cutting force signal measurements, semiconductor strain gauges are found to provide better sensitivity and accuracy as compared to metal foil. However, for overall continuous machining operation, especially in industrial applications, metal foil is still the more favorable option due to its consistency and stability in measurements.

(d) Strain gauges are available in a variety of physical and electrical characteristics in the market. More studies should be carried out utilising different brands or types of semiconductor strain gauges in order to find more accurate and stable sensors that are less susceptible to drift as potential replacements to metal foil in tool condition monitoring. An optimized machining parameter should also be used to ensure a consistent tool wear behavior for comparison.

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