

## Review Article

# A review of sensor-based cutting force measurement in machining: From microcontroller systems to smart manufacturings

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**ABSTRACT:** Cutting force is a key indicator that reflects the mechanical interaction between the cutting tool and the workpiece during machining. It directly influences energy consumption, tool wear, process stability, and machined surface quality. As modern manufacturing increasingly demands efficient, flexible, and sustainable production systems, the development of adaptive, real-time, and cost-effective cutting force measurement technologies has become essential. Previous review studies have primarily focused on cutting force modelling and commercial dynamometer systems, while limited attention has been given to the integration of low-cost sensors, microcontrollers, Internet of Things (IoT) technologies, and smart manufacturing applications. This review aims to evaluate recent developments in sensor- and microcontroller-based cutting force measurement systems and their potential integration within Industry 4.0 environments. The review synthesizes more than 230 references, primarily published between 2020 and 2026, together with selected earlier studies that provide important theoretical and technological foundations. Four main aspects are discussed: (1) theoretical foundations of cutting force, (2) sensor technologies and measurement system architectures, (3) modelling and data analysis methods, and (4) challenges and future development trends. The findings indicate that load cell and strain gauge sensors provide economical and practical solutions for long-term monitoring, whereas piezoelectric sensors remain the preferred option for high-frequency dynamic measurements due to their superior sensitivity and bandwidth. Furthermore, the integration of microcontrollers, IoT connectivity, machine learning, and digital twin technologies is accelerating the development of intelligent machining systems for smart and sustainable manufacturing.

**Keywords:** *Cutting force measurement, Microcontroller-based systems, Machining monitoring, Smart manufacturing, Industry 4.0*

## 1. INTRODUCTION

Machining remains one of the most widely used manufacturing methods in modern industry, particularly for producing components with high dimensional accuracy and surface quality [1]. Although significant advances have been made in the development of machine tools, cutting tool materials, and control systems, the material cutting process fundamentally involves a complex physical interaction between the cutting tool and the workpiece [2]. This interaction occurs under high stress and temperature conditions and is highly dynamic in nature.

Among the various variables in the machining process, cutting force plays a very important role because it directly reflects the mechanical response of the material to the cutting process [3]. The magnitude of cutting force affects the load received by the cutting tool and the machine tool, and is closely related to tool wear, geometric accuracy, and the surface quality of the machined component [4]. Excessive cutting force can accelerate tool failure and increase the risk of damage to machine components, while fluctuations in cutting force are often associated with process insta-

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**Received:** May 6, 2026

**Revised:** May 26, 2026

**Accepted:** June 17, 2026

**How to cite:** Ginting, Y. R., Br Ginting, S. L., Sutono, Romy, Aulia, M. L., (2026). A review of sensor-based cutting force measurement in machining: from microcontroller systems to smart manufacturing. *Journal of Applied Materials and Technology*, 8(1), 21-40. <https://doi.org/10.31258/Jamt.8.1.21-40>.

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bility, such as chatter vibration [5–7]. In addition to mechanical aspects, cutting force is also directly related to energy consumption in the machining process [8–10]. The cutting power required during cutting is the product of cutting force and cutting speed [9]. Therefore, cutting force is often used as an indirect indicator for evaluating the energy efficiency and sustainability performance of the machining process [11]. In the context of sustainable manufacturing, cutting force monitoring has become increasingly relevant because it enables the optimisation of cutting parameters to reduce energy consumption and extend tool life [11].

Conventionally, cutting force measurement is conducted using multi-axis piezoelectric dynamometers, which offer high accuracy and resolution [12]. However, cutting force measurement using piezoelectric dynamometers is generally expensive, involves relatively large equipment, and is more suitable for laboratory environments [13]. These limitations hinder the widespread deployment of commercial dynamometers in industrial production environments, particularly for continuous monitoring on production machines.

The development of sensor technology and embedded systems has encouraged the emergence of alternative approaches to cutting force measurement [15]. Sensors such as load cells, strain gauges, and piezoelectric sensors can now be integrated with low-cost microcontrollers [16]. Microcontroller platforms enable real-time cutting force data acquisition, basic signal processing, and data communication with external systems for monitoring and further analysis [17].

Unlike studies that focus on a single machining process, this review intentionally covers a wide range of machining operations, including turning, milling, micro-machining, and the machining of difficult-to-cut materials. This broader scope was adopted because cutting force characteristics, sensor requirements, measurement strategies, and implementation challenges can differ substantially across machining processes. By considering multiple machining applications, this review provides a more comprehensive understanding of sensor- and microcontroller-based cutting force measurement systems and their role in modern manufacturing.

## 2. RESEARCH GAP AND REVIEW CONTRIBUTION

Although numerous review articles have discussed cutting forces, commercial dynamometers, and machining process monitoring, most previous studies have primarily focused on cutting mechanics, cutting force prediction models, or the use of high-precision piezoelectric dynamometers [18, 38, 64]. Furthermore, most existing reviews examine sensor technologies separately and do not comprehensively integrate the development of low-cost sensor based measurement systems with modern microcontroller platforms [71, 76, 191].

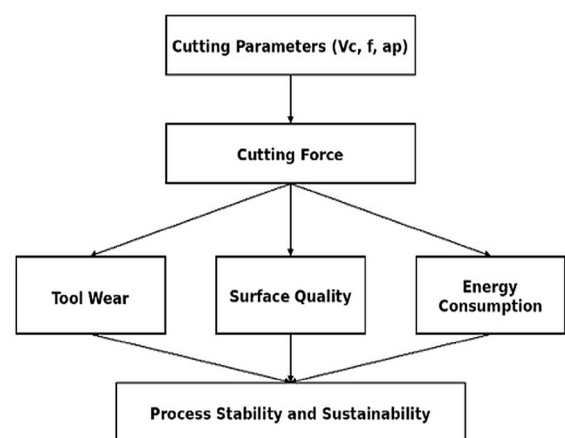
The rapid advancement of microcontrollers, the Internet of Things (IoT), and Industry 4.0 concepts has created new opportunities for the development of cutting force measurement systems that are more flexible, modular, and cost-effective [72, 73, 192–196]. Nevertheless, there remains a limited number of reviews that specifically address the relationship between cutting force theory, sensor technologies, microcontroller-based system architectures,

data modelling approaches, and their integration with smart manufacturing environments [71, 76, 191].

Based on these considerations, this review aims to provide a comprehensive overview of sensor- and microcontroller-based cutting force measurement systems, including sensor characteristics, system architectures, data analysis approaches, implementation challenges, and future opportunities for the development of intelligent and sustainable manufacturing systems.

Based on this background, this review paper aims to present a comprehensive review of cutting force in machining processes, with a focus on sensor- and microcontroller-based measurement systems. The scope of discussion includes the theoretical foundations of cutting force, the factors that influence cutting force, measurement system technologies and architectures, and their role in supporting sustainable and smart manufacturing.

Figure 1 shows the general framework of the relationship between machining, cutting force, sensor- and microcontroller-based measurement systems, and their use in analysis and smart manufacturing. The structure of this review follows the conceptual framework shown in Figure 1, beginning with the theoretical foundations of cutting force, followed by sensor and microcontroller-based measurement systems, modelling approaches, and future developments toward smart manufacturing.

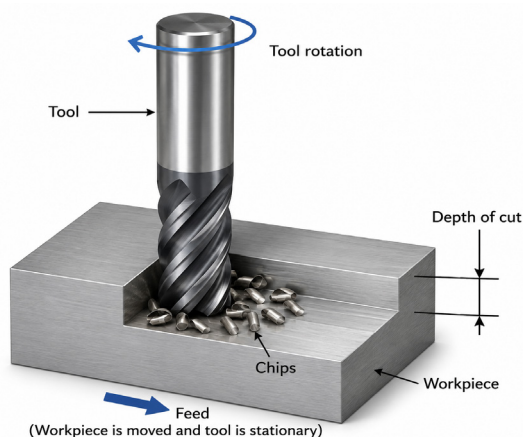


**Figure 1.** Conceptual diagram of the relationship between cutting force, measurement systems, and analysis in the machining process [Developed by the authors].

## 3. THEORETICAL FOUNDATIONS OF CUTTING FORCE IN MACHINING

**3.1. Definition and components of cutting force.** Cutting force is defined as the force acting on the cutting tool during the material removal process [18]. This force arises from the resistance of the workpiece material to plastic deformation and fracture, as well as from the frictional forces occurring at the tool–chip and tool–machined surface interfaces [18]. In practice, cutting force does not act as a single force, but rather as the resultant of several force components [20, 21]. In general, cutting force can be resolved into three main mutually perpendicular components. The first component is the tangential force, or main cutting force,

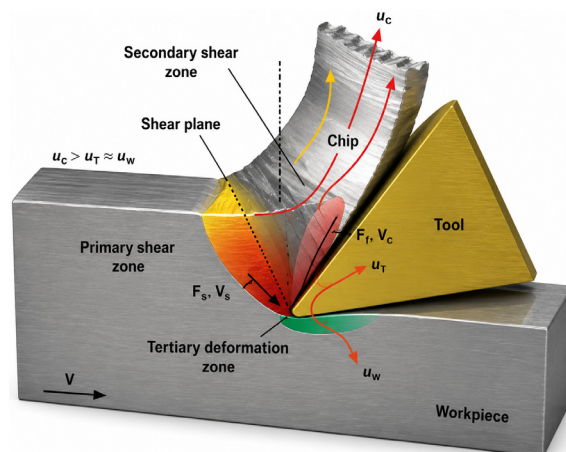
which acts in the direction of the cutting speed and contributes the largest portion of power consumption. The second component is the radial force, or thrust force, which acts perpendicular to the workpiece surface and affects tool deflection as well as dimensional accuracy. The third component is the axial force, or feed force, which acts in the direction of feed motion and influences process stability and chip formation [21, 22]. The cutting process and the interaction between the rotating cutting tool and the workpiece can be represented schematically, as shown in Figure 2. This interaction gives rise to the cutting force, which can be resolved into tangential ( $F_c$ ), radial ( $F_r$ ), and feed ( $F_f$ ) components.



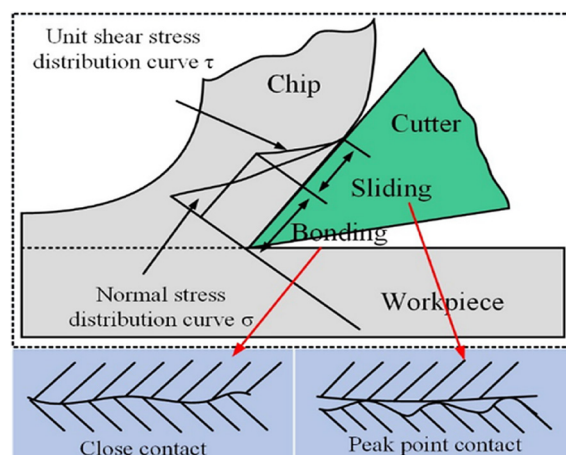
**Figure 2.** Schematic illustration of the end milling process showing tool rotation, feed direction, depth of cut, chip formation, and the interaction between the cutting tool and the workpiece.

The magnitude of each cutting force component is governed by multiple interacting factors, including the machining process type, cutting parameters, tool geometry, workpiece material properties, and the cooling and lubrication conditions employed during machining [18, 23, 25]. In turning processes, the tangential force is generally dominant, whereas in milling processes, the cutting force is discontinuous and varies over time according to the tool engagement angle and the number of cutting teeth [27–29].

**3.2. Mechanism of cutting force formation.** The formation of cutting force is essentially governed by two main mechanisms, namely the plastic deformation of the material in the shear zone and the frictional force at the tool–chip and tool–workpiece interfaces [30, 31]. During machining, the material in front of the tool tip undergoes intensive plastic deformation along the shear plane until it separates in the form of a chip [32]. The resistance of the material to this deformation contributes significantly to the magnitude of the cutting force [31]. To clarify the mechanism of plastic deformation occurring in the shear zone, an illustration of the chip formation process is shown in Figure 3. In addition to shear deformation, frictional force also plays an important role in the formation of cutting force [32, 33]. The formed chip slides along the rake face of the cutting tool, thereby generating frictional force due to adhesion and ploughing mechanisms [34]. Contact between the flank face of the tool and the machined surface also produces additional frictional force, particularly when the tool undergoes wear [2]. The frictional interaction between the chip



**Figure 3.** Mechanism of cutting force formation, illustrating the shear plane, plastic deformation zones, chip formation, and friction at the tool–chip and tool–workpiece interfaces.



**Figure 4.** Frictional force at the tool–chip interface, illustrating chip flow along the rake face and the frictional interaction that occurs [35].

and the tool surface can be observed schematically, as shown in Figure 4. These two mechanisms interact with one another and are influenced by the cutting conditions, tool geometry, as well as lubrication and cooling conditions. Therefore, cutting force is often used as a key parameter for analysing the physical phenomena that occur during the machining process [36, 37].

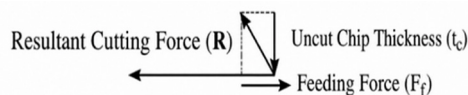
### 3.3. Classical and mechanistic models of cutting force.

To understand and predict cutting force, various theoretical and empirical models have been developed. One of the earliest and most widely used approaches is the orthogonal cutting model based on Merchant's theory [38]. The orthogonal cutting model relates cutting force to the shear angle, material shear stress, and friction angle on the rake face, thereby providing a fundamental understanding of the mechanics of chip formation [39].

To clarify the concept of the orthogonal cutting model, a schematic representation of the relationship between tool geometry, the shear plane, and force components is shown in Figure 5.

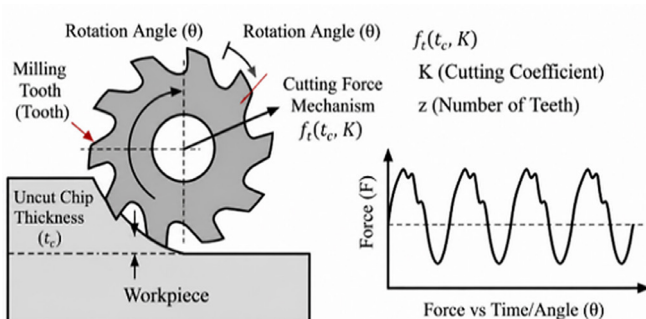
**Table 1.** Comparison of commonly used cutting force models.

Model Type	Main Assumption	Input	Output	Application	Limitation
Classical Orthogonal Cutting Model	Ideal two-dimensional cutting	Shear angle, friction angle, shear stress	Cutting force	Fundamental analysis of cutting mechanics	Assumptions are overly simplified
Mechanistic Cutting Force Model	Empirical cutting coefficients	Chip thickness, depth of cut	Cutting force components	Milling and industrial machining	Requires calibration
Data-Driven Cutting Force Model	Data-based relationships	Machining parameters and sensor data	Cutting force prediction	Monitoring and artificial intelligence (AI)	Requires large datasets

**Figure 5.** Classical orthogonal cutting model based on Merchant's theory, showing the resultant cutting force (R), feed force (Ff), and the uncut chip thickness (tc) [Developed by the authors].

However, classical models generally have limitations because they assume ideal and simplified cutting conditions [40]. In industrial practice, mechanistic models are more widely used because they are more flexible and applicable [41]. Mechanistic models express cutting force as a function of uncut chip thickness, cutting coefficients, and tool geometry parameters [42].

Mechanistic models are particularly useful in milling processes, where cutting force varies periodically with tool rotation [43, 44]. Although turning is commonly used to illustrate the fundamental mechanisms of cutting force formation, milling is also included in this review because it represents a machining process in which cutting forces vary continuously with time, thereby requiring measurement systems with enhanced dynamic data acquisition capabilities [22, 27, 28]. By combining mechanistic models with real-time cutting force measurement, it becomes possible to predict tool load, monitor tool wear, and detect abnormal cutting conditions [45, 46]. The periodic behaviour of cutting force in milling processes can be visualised through a mechanistic model, as shown in Figure 6.

**Figure 6.** Mechanistic cutting force model in the milling process, showing the influence of tool rotation angle ( $\theta$ ), number of teeth ( $z$ ), cutting coefficients ( $K$ ), and the variation in cutting force with time or rotation angle.

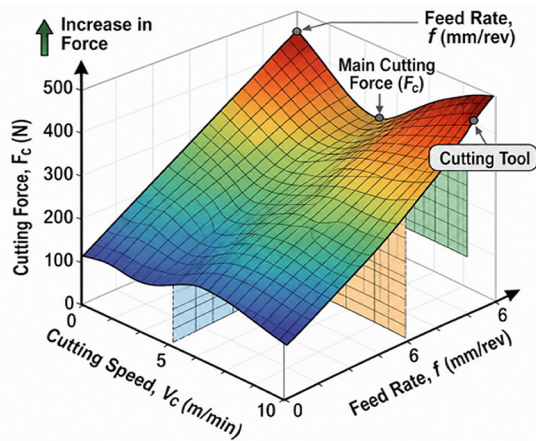
To facilitate a clearer understanding of the characteristics, assumptions, and applications of various cutting force modelling approaches, Table 1 compares the classical orthogonal model, mechanistic model, and data-driven model that are commonly employed in contemporary machining research and industrial applications. As shown in Table 1, classical orthogonal models are primarily useful for explaining the fundamental mechanics of cutting force formation, whereas mechanistic models offer improved predictive capability and practical applicability in industrial machining operations. In contrast, data-driven models have emerged as a promising approach for modern monitoring systems due to their ability to capture complex nonlinear relationships that are often difficult to describe using conventional physics-based models [18, 148, 149].

## 4. FACTORS AFFECTING CUTTING FORCE

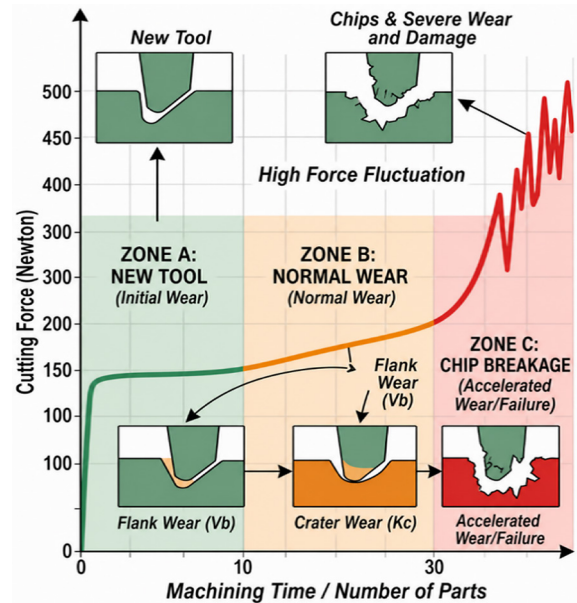
Numerous variables influence the generation of cutting force during machining operations. These variables can be broadly classified into cutting parameters, tool-related factors, workpiece material characteristics, machining conditions, and machine-tool dynamics. Since cutting force is the result of the interaction between these elements, a comprehensive understanding of their effects is necessary for accurate force prediction and effective process monitoring. The following subsections discuss the most significant factors affecting cutting force

**4.1. Cutting parameters.** Cutting parameters such as cutting speed, feed rate, and depth of cut have a direct influence on the magnitude of cutting force [18]. An increase in feed rate and depth of cut generally leads to an increase in cutting force because the volume of material removed becomes greater [47]. The effect of cutting speed is more complex, as it may reduce cutting force due to the thermal softening of the material or, conversely, increase it due to high strain-rate effects [48]. The interaction among cutting parameters also needs to be considered, because the effect of one parameter often depends on the values of the others [49]. Therefore, cutting force is frequently used as a primary response variable in machining process optimisation studies [49]. The interaction among cutting parameters in relation to cutting force can be visualised through a surface plot approach, as shown in Figure 7.

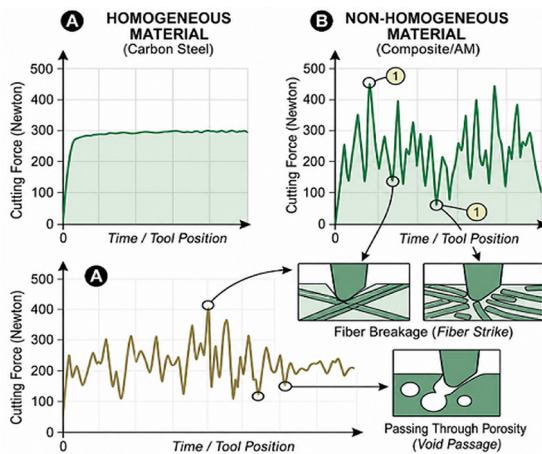
**4.2. Workpiece material properties.** The mechanical and thermal properties of the workpiece material, such as hardness, strength, ductility, and thermal conductivity, strongly influence cutting force [18]. Materials with high strength and hardness generally produce greater cutting forces [50]. Materials with low thermal conductivity tend to increase the cutting temperature, which



**Figure 7.** Visualisation of the influence of cutting parameters on cutting force using a surface plot, showing the interaction between cutting speed ( $V_c$ ) and feed rate ( $f$ ) on cutting force ( $F_c$ ), as well as its implications for machining process optimisation.



**Figure 9.** Relationship between the progression of tool wear and cutting force during the machining process [Developed by the authors].



**Figure 8.** Schematic illustration of cutting force fluctuations in homogeneous and non-homogeneous materials.

in turn affects frictional force and cutting force [51]. The influence of material homogeneity on cutting force stability can be illustrated as shown in Figure 8. In composite materials or additively manufactured materials, the structural non-homogeneity of the material can cause significant fluctuations in cutting force [52]. This indicates that the cutting force signal not only represents the mechanical load, but can also be used as an indicator of the internal characteristics of the material during the machining process [30, 51, 161]. These fluctuations can be utilised as information to identify material behaviour during machining [30, 161, 169]. For comparative cutting force measurements, the workpiece material should remain consistent because differences in mechanical and thermal properties can significantly affect the magnitude and characteristics of cutting force [30, 50, 51, 164].

**4.3. Tool geometry and condition.** The Tool geometry, including rake angle, clearance angle, and tool nose radius, has a major influence on cutting force [53]. A larger positive rake angle generally reduces cutting force because it facilitates chip flow [54].

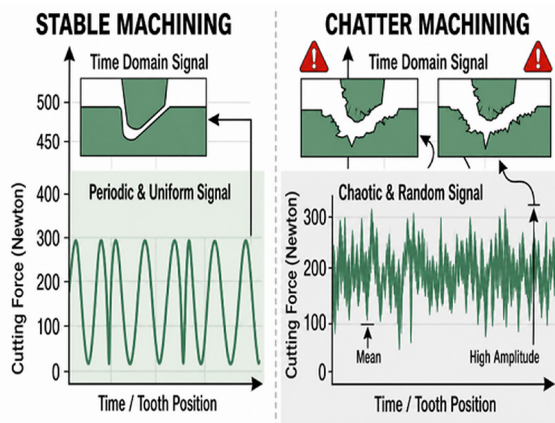
Conversely, a large tool nose radius can increase cutting force due to the increased ploughing effect, particularly in micro-machining [55, 56]. Tool wear alters the contact conditions and increases frictional force, thereby causing an increase in cutting force and its fluctuations [57]. The progression of tool wear and its effect on cutting force can be illustrated step by step, as shown in Figure 9. Therefore, cutting force monitoring is widely used as an indirect method for detecting tool condition and wear [58].

Cutting force sensors intended for tool wear monitoring typically require sufficient sampling rates and data acquisition capabilities to ensure that force variations resulting from wear progression can be detected accurately [46, 69, 161]. In industrial environments, load cells are commonly used for long-term condition monitoring because of their stability and cost-effectiveness, while piezoelectric sensors are preferred for capturing dynamic force variations and high-frequency fluctuations owing to their superior dynamic response [91–96, 105, 106]. Nevertheless, both approaches are subject to challenges such as signal noise, sensor drift, and temperature-induced sensitivity changes, which may adversely affect measurement accuracy [99, 102, 109].

This pattern indicates that cutting force can be used as an indirect indicator for monitoring tool condition in real time. A sharp and fluctuating increase in force generally serves as an early sign of critical wear or tool failure.

**4.4. Cooling, lubrication, and system dynamics.** Cooling and lubrication conditions influence cutting force through changes in frictional conditions and temperature in the cutting zone [18, 59]. Methods such as minimum quantity lubrication (MQL), cryogenic cooling, and dry machining produce different cutting force characteristics [59, 60].

In addition, the structural stiffness of the machine tool and vibration phenomena also affect cutting force [61]. Insufficient stiffness can amplify force fluctuations, while chatter unstable



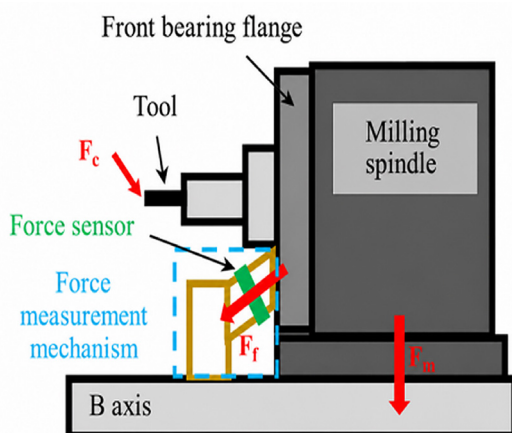
**Figure 10.** Comparison of cutting force signals under stable cutting and chatter conditions [Developed by the authors].

force signals [62]. These phenomena can be observed through the characteristics of the cutting force signal, as shown in Figure 10. Therefore, cutting force analysis provides important insights into both the static and dynamic aspects of the machining system [63].

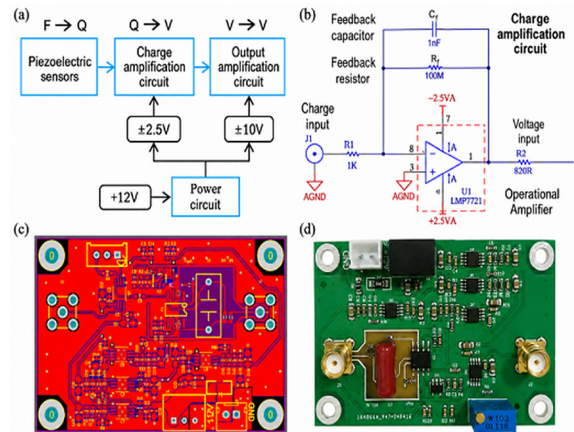
### 5. SENSOR- AND MICROCONTROLLER-BASED SYSTEMS CUTTING FORCE MEASUREMENT

Sensor based cutting force measurement systems can be broadly classified according to their sensing principles, including piezoelectric, strain-gauge, load-cell, optical, capacitive, and MEMS-based technologies. The following sections discuss the most widely adopted sensing approaches and their applications in machining force monitoring.

**5.1. Piezoelectric sensors and optical technology.** The principle of cutting force measurement based on elastic deformation can be illustrated as shown in Figure 11. This approach differs conceptually from commercial dynamometers, which are designed as integrated units with mechanical and electrical char-



**Figure 11.** Schematic of force sensor placement in a machining system [66].



**Figure 12.** Signal conditioning circuit (charge amplifier) in a force measurement system [67].

acteristics that have been factory-calibrated [67, 68]. Sensor and Microcontroller-Based Cutting Force Measurement Systems, design flexibility is a key feature, whereby sensors can be placed at various strategic points, such as the tool holder, machine table, or additional elastic elements specially designed for the purpose [69–71]. The main characteristics of sensor- and microcontroller-based cutting force measurement include:

1. Indirect measurement through plastic deformation.
2. Dependence on the mechanical design of the system.
3. High flexibility in configuration.
4. Relatively low system cost.

This approach makes sensor- and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems highly attractive for experimental research, prototype development, and process monitoring applications in educational settings and small- to medium-scale industries [72, 73].

**5.2. Architecture of sensor- and microcontroller-based cutting force measurement systems.** The architecture of a sensor- and microcontroller-based cutting force measurement systems is generally arranged in several integrated functional layers [16]. Each layer has a specific role in ensuring that mechanical force can be transformed into meaningful digital data [74, 75].

**5.2.1. General system structure.** In general, the measurement system consists of:

1. A supporting mechanical element.
2. A force sensor.
3. A signal conditioning circuit.
4. A microcontroller-based data acquisition unit.
5. Data processing and visualisation software.

The mechanical element functions as the medium for transferring cutting force to the sensor [76]. The design of this element strongly determines the sensitivity and linearity of the system [77]. The sensor then detects the deformation that occurs and generates an electrical signal with a relatively small amplitude [78]. This signal cannot be processed directly by the microcontroller without first passing through a signal conditioning stage [79, 80]. Therefore, amplification and filtering circuits become crucial components in the system architecture [81–84]. One example of the implementation of a signal conditioning circuit based on a

piezoelectric sensor is shown in Figure 12. Although the figure shows the use of a piezoelectric sensor with a charge amplifier, this signal conditioning principle also applies to other sensors, such as load cells, which generally use amplifier circuits based on a Wheatstone bridge and an instrumentation amplifier.

**5.2.2. Role of the microcontroller in the data acquisition system.** The microcontroller functions as the centre of data acquisition and processing [85, 86]. It reads the conditioned analogue signal through an analogue-to-digital converter (ADC), converts it into digital data, and then transmits it to an external device or stores it for further analysis [87, 88]. The advantages of a microcontroller include:

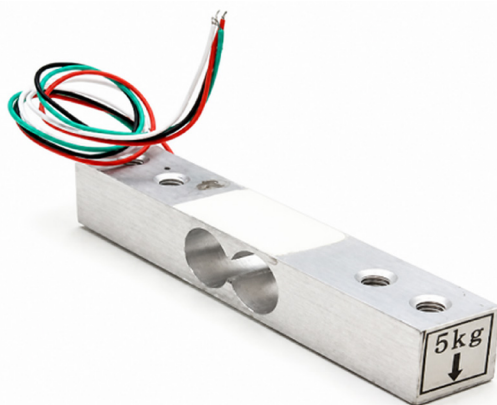
1. Ease of programming.
2. Compatibility with various sensor modules.
3. Broad community support.

However, limitations in built-in ADC resolution and processing speed must be taken into account in system design, particularly for dynamic machining applications [89].

**5.3. Sensors used in cutting force measurement.** Sensor selection is a key factor that determines the performance of a sensor- and microcontroller-based cutting force measurement systems [15]. Each type of sensor has different characteristics in terms of sensitivity, measurement range, and dynamic response [90].

**5.3.1. Strain gauge-based load cell.** The load cell is the most widely used sensor in sensor- and microcontroller-based cutting force measurement systems [91–95]. This sensor operates based on the principle of changes in strain gauge resistance due to elastic deformation [16]. The main characteristics of a load cell are:

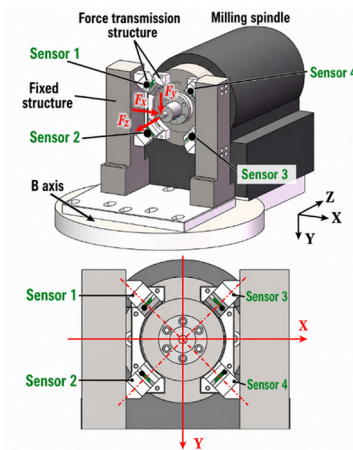
1. Suitable for static force measurement and low-frequency dynamic measurement.
2. Good long-term stability.
3. Easy integration with microcontrollers using amplifier modules.



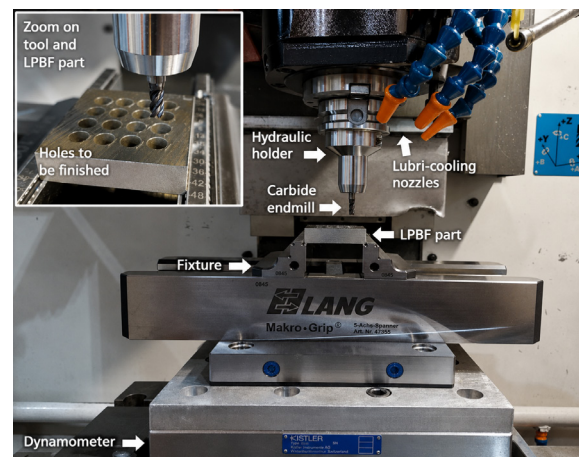
**Figure 13.** Small-sized load sensor [97].

However, load cells have limitations in responding to high-frequency force fluctuations, making them less suitable for analysing rapid cutting dynamics [97]. A typical example of a compact strain gauge-based load cell commonly used in sensor- and microcontroller-based cutting force measurement systems is shown in Figure 13.

**5.3.2. Discrete strain gauges.** Discrete strain gauges are often attached directly to the tool holder or machine structure [98, 99]. This approach provides high flexibility in system design and enables the measurement of very small deformations [101]. A representative arrangement of discrete strain gauges for multi-axis cutting force measurement is shown in Figure 14. Four strain gauges are positioned symmetrically on the force transmission structure to sense elastic deformation produced by machining forces, allowing the estimation of the cutting force components ( $F_x$ ,  $F_y$ , and  $F_z$ ). The configuration in the figure shows a multi-sensor system for three-directional force



**Figure 14.** Sensor placement configuration for cutting force measurement [67].



**Figure 15.** Piezoelectric cutting force dynamometer [107].

measurement. In this study, the measurement is focused on one or two directions by considering the limitations of the system and the objectives of the experiment. The main advantage of strain gauges is their high sensitivity. However, the installation of these sensors requires high precision and a complex calibration process [101]. In addition, strain gauges are highly sensitive to temperature changes and environmental noise [102].

**5.3.3. Piezoelectric sensors.** Piezoelectric sensors generate an electrical charge in response to mechanical force [104, 105]. These sensors are highly effective in detecting rapid changes in force

**Table 2.** Comparison of sensor technologies commonly used for cutting force measurement.

Sensor	Sensitivity	Frequency Response	Static Measurement	Cost	Integration Complexity	Application
Load Cell	High	Low–moderate	Very good	Low	Easy	Process monitoring and education
Strain Gauge	very high	Moderate	Good	Low-moderate	Moderate	Tool holder and machine structure
Piezoelectric	very high	Very high	Poor	High	High	Dynamic cutting analysis

and are suitable for analysing cutting force dynamics [105]. The main limitation of piezoelectric sensors is their inability to measure static force stably without additional circuitry. Therefore, their use in sensor- and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems requires a more complex electronic design [105]. A typical example of a commercial piezoelectric cutting force dynamometer used for high-precision cutting force measurement is shown in Figure 15.

To provide practical guidance for sensor selection, Table 2 summarizes the key characteristics of several sensor technologies commonly used in sensor- and microcontroller-based cutting force measurement systems, including their sensitivity, frequency response, integration complexity, cost, and typical applications. As shown in Table 2, load cells and strain gauges are widely adopted in sensor- and microcontroller-based cutting force measurement systems because they provide a favorable balance between cost, measurement capability, and integration simplicity [76, 91–101]. Conversely, piezoelectric and optical sensors exhibit superior dynamic performance and higher frequency response, although they typically involve greater implementation complexity and higher system costs due to the requirements for advanced signal conditioning and data acquisition hardware [76, 91–106, 171].

**5.4. Signal conditioning and analogue-to-digital conversion.** The output signals from force sensors generally have very small amplitudes and are susceptible to interference [83, 108–110]. Therefore, signal conditioning is a crucial stage in determining the quality of the cutting force data obtained [111].

**5.4.1. Signal amplification and filtering.** Instrumentation amplifier circuits are used to increase the signal amplitude without significantly amplifying noise [112, 113]. In addition, signal filtering is required to separate the cutting force components from irrelevant high-frequency disturbances [114]. Filtering can be performed through:

1. Analogue circuits, such as low-pass filters.
2. Digital signal processing on the microcontroller.

**5.4.2. ADC resolution and limitations.** The built-in ADCs of microcontrollers generally have limited resolution. Therefore, for certain applications, external ADC modules with higher resolution are required [87]. ADC resolution strongly affects the ability of the system to detect small changes in cutting force [114]. ADC selection should consider:

1. Resolution.
2. Sampling rate.
3. Compatibility with the microcontroller system.

**5.5. Calibration of the cutting force measurement system.** Calibration is an important stage to ensure that the electrical signals obtained can be converted into accurate force values [109, 115–117]. Calibration is carried out by applying a known force load and

recording the system response [116].

**5.5.1. Static calibration.** Static calibration is performed by applying force incrementally to the sensor and establishing a linear relationship between force and the output signal [116–118]. An effective calibration curve typically demonstrates a linear relationship between the applied force and the corresponding sensor output signal. A high degree of linearity is essential to ensure accurate conversion of electrical signals into meaningful force measurements. Previous studies on the calibration of load cell- and strain gauge-based force sensors have shown that properly implemented calibration procedures can achieve stable and reliable measurement performance over the intended operating range [115–117, 120, 122]. The calibration factor obtained is then used to convert the data during the machining process.

**5.5.2. Dynamic calibration and validation.** In addition to static calibration, dynamic validation is required to evaluate the system response to rapid changes in cutting force [119]. Dynamic validation ensures that the microcontroller-based system is capable of recording cutting force fluctuations representatively [110, 120].

**5.6. Sensor and microcontroller-based cutting force measurement systems.** The performance of a sensor- and microcontroller-based cutting force measurement systems is influenced by a combination of mechanical, electronic, and programming factors. Microcontroller-based data acquisition systems exhibit varying capabilities with respect to analog-to-digital converter (ADC) resolution, sampling rate, and computational capacity [85, 87, 115]. The performance of cutting force measurement systems is highly dependent on the ADC's ability to resolve small signal variations and on the sampling rate employed to accurately capture dynamic events occurring during machining operations [110, 114, 138, 139].

To enhance measurement performance, some cutting force measurement systems incorporate external ADCs that provide higher resolution than the built-in converters available in conventional microcontrollers [114]. By contrast, commercial dynamometer systems are typically equipped with high-precision data acquisition hardware and superior dynamic response capabilities, making them more suitable for high-frequency cutting force measurements [122–126]. Consequently, the choice of data acquisition platform should be aligned with the resolution requirements, bandwidth demands, and dynamic characteristics of the machining process under investigation. In general, this microcontroller-based system is capable of providing consistent cutting force trends, although its absolute values may differ from those obtained using commercial dynamometers [121]. The main characteristics of the system include:

1. Real-time monitoring capability.
2. Configuration flexibility.
3. Limitations in absolute accuracy [110].

**Table 3.** Approximate Cost Comparison of Cutting Force Measurement Systems.

System	Approximate Cost (USD)	Typical application
Arduino + Load Cell	20-100	Education, experimental research, process monitoring
Arduino + Strain Gauge	50-200	Custom tool holders, laboratory prototypes
Arduino + Piezoelectric Sensor	100-500	Dynamic force measurement prototypes
Commercial Piezoelectric Dynamometer (e.g., Kistler)	5,000-30,000+	Industrial research and high-precision laboratory measurements

### 5.7. Comparison with conventional dynamometers.

Commercial piezoelectric dynamometers. They remain the standard in cutting force research due to their high accuracy and bandwidth [122]. Sensor- and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems, however, are advantageous in terms of flexibility and low cost [73]. In addition to their flexibility, sensor- and microcontroller-based cutting force measurement systems are generally regarded as a more economical alternative to commercial dynamometers because they can be implemented using widely available sensors and low-cost embedded platforms [72, 73]. In contrast, commercial dynamometer systems are specifically designed for high-accuracy cutting force measurement and typically involve more sophisticated sensing elements, signal conditioning circuits, and calibration procedures [122–126]. A qualitative comparison of implementation costs is presented in Table 3. The values presented in Table 3 are intended to provide a qualitative indication of relative cost levels between different cutting force measurement approaches based on information reported in the literature and manufacturer documentation [71, 73, 122–126]. The main comparison between the two approaches can be summarised as follows:

1. Dynamometers are superior in terms of accuracy and dynamic response [123–126].
2. Sensor- and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems are superior in terms of flexibility and low cost [73, 128–130].
3. Sensor- and microcontroller-based cutting force measurement systems are particularly suitable for long-term process monitoring, educational applications, and cost-sensitive implementations because they provide flexible data acquisition capabilities and can be integrated with widely available embedded platforms [72, 73, 130].

Thus, sensor- and microcontroller-based cutting force measurement systems should be regarded as a complementary alternative to conventional dynamometers. While commercial dynamometers remain preferable for applications requiring the highest accuracy and dynamic response, sensor- and microcontroller-based systems offer practical advantages in terms of flexibility, accessibility, and ease of integration for monitoring and research purposes [122–126].

## 6. MODELLING AND DATA ANALYSIS OF CUTTING FORCE

Sensor and microcontroller-based cutting force measurement not only produces numerical data, but also provides opportunities to develop predictive models and more in-depth process analysis [15, 110, 131]. The cutting force data obtained during machining are dynamic, non-linear, and influenced by various process parameters and material characteristics [131]. Therefore, modelling and data analysis approaches form an integral part of the utilisation of sensor and microcontroller-based cutting force measurement systems [131–134].

**6.1. Characteristics of cutting force data.** Cutting force data recorded through sensor and microcontroller-based cutting force measurement systems are generally in the form of time-series signals that describe changes in force during the cutting process [97]. These signals have several main characteristics:

1. They are dynamic and vary over time.
2. They contain periodic components, particularly in milling processes.
3. They are affected by mechanical and electrical noise.
4. They reflect the complex interaction between the cutting tool and the chip formation process.

In continuous turning processes, cutting force signals tend to be more stable, with small fluctuations caused by material non-homogeneity or tool wear [135]. In contrast, in milling processes, cutting force exhibits a periodic pattern that follows tool rotation and the number of cutting teeth [136]. This pattern provides important information about the load on each tooth and the force distribution during one cutting cycle.

In sensor and microcontroller-based cutting force measurement systems cutting force measurement systems, data quality is strongly influenced by ADC resolution, sampling rate, and the filtering method used [137–140]. Therefore, understanding the characteristics of the signal is an initial step before further modelling is carried out [141].

### 6.2. Analytical and mechanistic modelling approaches.

Analytical approaches in cutting force modelling are generally based on the theory of metal cutting mechanics [142, 143]. Classical models, such as orthogonal cutting, relate cutting force to material shear stress, shear angle, and friction angle on the rake face [144]. Although this model provides a strong conceptual understanding, its application in sensor and microcontroller-based cutting force measurement systems is more commonly used as a validation reference rather than as the main model.

A more practical approach is the mechanistic model [145–146]. In this model, cutting force is expressed as a function of uncut chip thickness, depth of cut, and cutting coefficients [143]. These coefficients are usually obtained through experiments and can be estimated using data collected by sensor and microcontroller-based cutting force measurement systems [131].

The advantage of the mechanistic model lies in its ability to accommodate various machining conditions without requiring ideal assumptions that oversimplify the process [148]. In the context of sensor and microcontroller-based cutting force measurement systems cutting force measurement systems, this model enables parameter calibration based on actual data obtained in real time [149].

**Table 4.** Summary of representative studies on cutting force modelling and data analysis.

Author	Method	Objective
Liu et al. [20]	Machine Learning Review	Cutting force prediction
Cheng et al. [151]	Deep Neural Network	Cutting force prediction from CNC signals
Ni et al. [152]	Hybrid Mechanism–Data Model	Milling force prediction
Bernini et al. [160]	Data-driven Monitoring	Monitoring of milling process conditions
Ren et al. [161]	Machine Learning + Cutting Mechanics	Identification of dynamic machining equations
Xu et al. [163]	Machine Learning	Cutting force prediction in milling FGM

**6.3. Signal analysis and feature extractions.** In addition to theory-based modelling, signal analysis plays an important role in interpreting cutting force data [148, 149]. This analysis process aims to extract important features that represent machining conditions [150, 151]. Several commonly analysed parameters include:

1. Mean cutting force.
2. Maximum and minimum values.
3. Standard deviation.
4. Dominant frequency components.

Frequency-domain analysis, for example through Fourier transform, can identify the presence of vibration or chatter reflected in the cutting force signal [152, 153]. In sensor and microcontroller-based cutting force measurement systems cutting force measurement systems, further analysis is often carried out on an external computer after the data are transmitted through serial communication or wireless modules [85]. Feature extraction enables the complexity of raw data to be reduced into parameters that can be more easily used in predictive models or condition monitoring systems [154–156].

**6.4. Data-driven and machine learning approaches.** With the increasing availability of continuously recorded cutting force data, data-driven approaches have become increasingly relevant [45, 157]. Machine learning-based models are capable of capturing non-linear relationships between cutting parameters and cutting force without requiring explicit physical formulations [45, 158–160]. In the context of sensor and microcontroller-based cutting force measurement systems cutting force measurement systems, cutting force data can be used as:

1. Input for training predictive models.
2. An indicator of tool condition.
3. A feedback parameter in adaptive control systems.

Although microcontrollers have limitations in performing complex computational processing, these systems can function as data acquisition devices connected to more powerful computing platforms [73, 88]. Thus, the integration of low-cost sensor systems and data-driven analytics provides opportunities for the development of smart machining based on cutting force monitoring [161, 162]. Recent studies have increasingly adopted data-driven and machine learning approaches for cutting force prediction, tool condition monitoring, process instability detection, and the enhancement of machining model accuracy [18, 148, 149, 157–160]. Table 4 presents a summary of representative studies that combine data-driven techniques with cutting force analysis.

As shown in Table 4, machine learning approaches have evolved from purely data-driven predictive models toward hybrid frameworks that combine cutting mechanics with artificial intelligence techniques. Such approaches offer improved prediction accuracy while preserving a stronger physical interpretation of the machining phenomena compared with conventional black-box models [148, 149, 158, 234].

## 7. CUTTING FORCE IN SPECIAL MACHINING PROCESSES

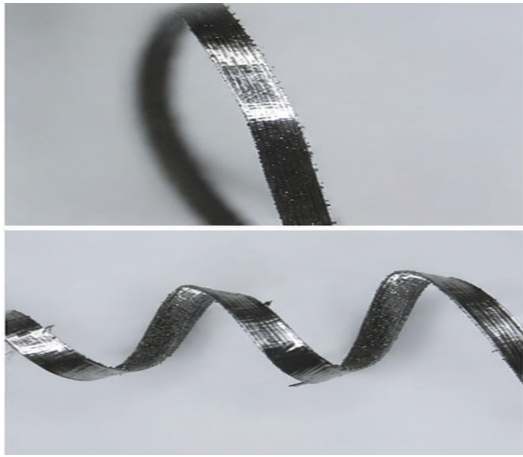
The behaviour of cutting force is not always uniform across all types of machining processes [18, 142]. Under certain conditions, cutting force characteristics can change significantly due to the process scale, material type, or cutting strategy used [163].

**7.1. Micro-machining and scale effects.** In micro-machining, the uncut chip thickness approaches the size of the tool nose radius [164]. This condition gives rise to a phenomenon known as the size effect, in which the specific cutting energy increases significantly [165]. In this context, the measured cutting force is often greater than that predicted by conventional models [166]. In addition, cutting force fluctuations become more dominant due to high sensitivity to small variations in geometry and material properties [167, 168]. Microcontroller-based measurement systems in micro-machining must have:

1. High sensitivity [169].
2. Adequate ADC resolution [114].
3. Effective noise filtering [170].

**7.2. Machining of difficult-to-cut materials.** Materials such as titanium alloys, Inconel, and composites have mechanical and thermal characteristics that result in high cutting forces and complex temperature distributions [171]. In composite materials, structural anisotropy causes cutting force to vary along the cutting direction [172]. Cutting force measurement in these materials provides important insights into damage mechanisms and tool–material interaction [15, 173, 174]. Sensor and microcontroller-based cutting force measurement systems enable experimental observation with high flexibility, particularly in studies involving alternative cutting parameters [175]. Typical examples of difficult-to-cut materials commonly investigated in cutting force studies are presented in

**Figure 16.** Segmented chip formation during the machining of a titanium alloy [176].



**Figure 17.** Serrated chip formation during the machining of an inconel alloy [177].

Figures 16 and 17. Titanium alloys commonly generate segmented chips, whereas Inconel alloys tend to produce serrated chips due to their high strength, low thermal conductivity, and severe plastic deformation during cutting. These characteristic chip formations are closely associated with high cutting forces, elevated cutting temperatures, and accelerated tool wear, making them important indicators for analysing machining performance.

**7.3. High-speed machining and force dynamics.** In high-speed machining, cutting force is influenced by strain-rate effects and the dynamics of the machine system [175]. Cutting force fluctuations may increase due to structural vibration and the dynamic interaction between the cutting tool and the workpiece [18, 61]. Under these conditions, sampling rate becomes a critical factor. Sensor and microcontroller-based cutting force measurement systems must be designed by considering processing capability limitations so that they remain able to record force variations representatively [178, 179].

## 8. CUTTING FORCE AND SURFACE INTEGRITY

Cutting force is not only related to the mechanical load during the machining process, but also plays a role in determining the quality and integrity of the machined surface [18]. The relationship between cutting force and surface integrity is complex and is influenced by process parameters and tool condition [180].

**8.1. Relationship with surface roughness.** In general, an increase in cutting force is often accompanied by an increase in surface roughness [18]. High cutting force can cause greater plastic deformation and instability in the tool-workpiece contact [181]. Real-time cutting force monitoring enables the identification of machining conditions that may potentially produce surfaces of low quality [71, 182–184]. Thus, cutting force can be used as an indirect indicator for surface quality control [110].

**8.2. Residual stress and microstructural changes.** In large cutting forces, particularly when combined with high temperatures, can generate residual stress on the workpiece surface [185]. This residual stress affects the fatigue life of components and their long-term structural performance [186]. Cutting force information obtained through sensor systems can be used as a supporting parameter in evaluating the risk of thermal deformation and microstructural changes [13, 15].

### 8.3. Role of cutting force in surface integrity monitoring.

The By integrating cutting force data with other process parameters, it is possible to develop an indirect surface integrity monitoring system [182, 187, 188]. This approach is more efficient than direct measurement of roughness or residual stress, which requires additional equipment [189, 190]. In the context of sensor and microcontroller-based cutting force measurement systems cutting force measurement systems, cutting force data can become part of an integrated monitoring system that supports data-driven decision-making during the machining process [71, 184, 191].

## 9. INTEGRATION OF CUTTING FORCE MEASUREMENT IN SMART MANUFACTURING AND INDUSTRY 4.0

The development of modern manufacturing towards the Industry 4.0 paradigm requires the integration of physical and digital systems through data connectivity, intelligent analytics, and real-time information-based automation [192–194]. In this context, cutting force measurement is no longer viewed merely as a laboratory-based experimental activity, but as an important element in adaptive and connected smart manufacturing systems [188, 191, 195, 196]. Sensor and microcontroller-based cutting force measurement systems have significant potential to support this transformation, particularly at a flexible and affordable implementation level [15, 121, 197]. As an open platform, the microcontroller enables integration with various communication modules, such as Wi-Fi, Bluetooth, and certain industrial protocols [198]. Thus, cutting force data can be transmitted in real time to a local server or cloud-based platform for further analysis [199–201]. Within the smart manufacturing framework, cutting force data can be utilised for [202]:

1. Continuous process condition monitoring.
2. Early detection of tool wear.
3. Adaptive control of cutting parameters.
4. Optimisation of energy consumption.

This integration enables machining systems to operate more responsively to changes in process conditions [203]. For example, when cutting force increases beyond a certain threshold, the system can automatically adjust the feed rate or cutting speed to maintain process stability [195, 204, 205]. Furthermore, the concept of cyber-physical systems provides opportunities for developing machining systems that combine predictive models with actual sensor data [206, 207]. In this context, the microcontroller functions as the data acquisition layer, while advanced analytics are performed on a more powerful computing system [73, 208, 209]. This approach creates a more transparent and data-driven machining ecosystem [210, 211].

**9.1. Digital twin and data-driven monitoring.** In One important development direction in smart manufacturing is the concept of the digital twin, which refers to a digital representation of a physical system that is updated in real time based on sensor data [212–214]. In machining, a digital twin enables the simulation of process conditions simultaneously with the actual operation of the machine [215–217]. Cutting force data obtained from sensor and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems can serve as a key parameter in updating the digital model [15, 197]. By incorporating actual data into the model, differences between ideal and real operating conditions can

be identified more quickly [218]. The benefits of this approach include [219, 220]:

1. Improved accuracy in predicting process performance.
2. Evaluation of tool condition without stopping the machine.
3. Reduced risk of sudden failure.

Although full implementation of a digital twin requires more complex computing and communication infrastructure, microcontroller-based sensor systems can provide an economical initial foundation for the development of such systems [221–223].

**9.2. Energy efficiency and process sustainability.** Sustainability aspects in manufacturing have received increasing attention, particularly in relation to energy consumption and process efficiency [224, 225]. Cutting force is directly related to the cutting power required by the machine [18]. An increase in cutting force is generally followed by an increase in energy consumption [49]. By monitoring cutting force in real time, it is possible to evaluate the most energy-efficient cutting parameters [45, 49]. Sensor and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems allow repeated experiments to identify parameter combinations that produce minimum cutting force without compromising surface quality [226]. The contribution of this system to sustainability includes [227–229]:

1. Reduction of specific energy consumption.
2. Extension of tool life.
3. Minimisation of material waste caused by surface defects.

## 10. CHALLENGES IN CUTTING FORCE MEASUREMENT AND MODELLING

Although sensor and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems offer high flexibility, several technical and methodological challenges need to be considered to ensure that the system can produce reliable results.

**10.1. Challenges at the micro scale and in high-dynamic conditions.** In micro-machining or high-speed processes, cutting force variations occur within a very short time scale [230]. Limitations in ADC resolution and microcontroller sampling rate may restrict the ability of the system to capture transient phenomena. In addition, at the micro scale, environmental noise and machine vibration can have amplitudes comparable to the measured force signal [109, 231]. This requires very careful mechanical and electronic design to ensure that the signal-to-noise ratio remains adequate.

**10.2. Limitations in absolute accuracy.** Compared with commercial dynamometers, sensor and Microcontroller-Based Cutting Force Measurement Systems cutting force measurement systems generally have lower absolute accuracy [117]. Factors such as imperfect calibration, temperature drift, and sensor non-linearity can affect measurement results [232]. However, in many monitoring applications, the relative trend of cutting force is more important than its absolute value [233]. Therefore, understanding the purpose of the application is key to determining whether a microcontroller-based system is adequate [73].

**10.3. Generalisation of predictive models.** Cutting force models developed based on specific experimental data often have limitations in their generalisation to different conditions [234, 235]. Variations in material, tool geometry, and machine configuration can produce significantly different force behaviour [181, 236]. The devel-

opment of adaptive models that are capable of learning from new data is both a challenge and an opportunity in sensor based cutting force research [46, 175].

**10.4. Future research directions.** Cutting Several promising development directions in sensor and microcontroller-based cutting force research include [175]:

1. Improving data acquisition resolution and speed.
2. Integrating artificial intelligence-based computing.
3. Developing low-cost multi-axis modules.
4. Fully integrating the system with smart manufacturing systems

Future research may also focus on the design of sensor structures that are stiffer while remaining sensitive, thereby improving accuracy

## 11. CONCLUSION

The Cutting force is a fundamental parameter in machining processes that reflects the complex interaction between the cutting tool and the workpiece. A comprehensive understanding of cutting force characteristics is essential for ensuring process stability, surface quality, energy efficiency, and tool life. The development of sensor and microcontroller-based measurement systems provides a flexible and economical alternative to conventional dynamometers. Although these systems have limitations in terms of absolute accuracy and dynamic bandwidth, they show considerable potential for real-time monitoring applications, experimental research, and integration with smart manufacturing systems. The main findings of this review indicate that:

1. Load cell and strain gauge sensors represent the most economical and easily implementable solutions for sensor and microcontroller-based cutting force measurement systems, particularly for process monitoring, experimental research, and educational applications.
2. Piezoelectric sensors remain the preferred choice for high-frequency dynamic cutting force measurements due to their superior sensitivity and bandwidth compared with resistive-based sensing technologies.
3. Advances in modern microcontrollers have enabled the implementation of real-time cutting force monitoring systems at significantly lower cost than commercial dynamometers, thereby creating broader opportunities for deployment in small and medium-sized manufacturing enterprises.
4. The integration of Internet of Things (IoT), machine learning, and digital twin technologies has emerged as a major development direction for cutting force measurement systems, enabling the realization of more adaptive, connected, and data-driven machining systems within the Industry 4.0 framework.

Through the combination of experimental measurement, theory and data-driven modelling, and integration with digital technologies, sensor and microcontroller-based cutting force measurement systems can serve as a foundation for the development of adaptive, intelligent, and sustainable machining systems. Existing challenges provide opportunities for further research, particularly in improving data acquisition quality, developing more generalisable predictive models, and integrating these systems into the Industry 4.0 ecosystem. Thus, sensor and microcontroller-based approaches are not only relevant as low-cost technical solutions, but also represent a strategic step towards smarter, more efficient, and sustainability-oriented machining systems.

## ■ ACKNOWLEDGEMENTS

The authors would like to thank the Department of Mechanical Engineering, Universitas Riau, for providing academic support and access to scientific resources that facilitated the completion of this review. The authors also appreciate the valuable comments and suggestions provided by the reviewers and editors, which helped improve the quality of this manuscript.

## ■ CREDIT AUTHOR STATEMENT

**Yogie Rinaldy Ginting:** Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing. **Selvia Lorena Br Ginting:** Methodology, Formal Analysis, Writing-Reviewing and Editing. **Sutono:** Investigation, Data Curation, Validation, Writing-Reviewing and Editings. **Romy:** Visualization, Resources, Validation, Writing-Reviewing and Editing. **Mega Luvita Aulia:** Data Investigation, Literature Review, Data Curation, Formal Analysis, Visualization, Writing-Original Draft Preparation.

## ■ DECLARATIONS

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## ■ AVAILABILITY OF DATA

No new data were generated or analyzed in this study. Accordingly, no datasets are associated with this manuscript.

## ■ AI DISCLOSURE STATEMENT

The authors declare that no Generative AI tools were used in the preparation, writing, analysis, or editing of this manuscript.

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