UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 10, No. 4, 2024

Serhiy Pasternak[1], Vadym Stupnytskyy[2]

[1] Department of Robotics and Integrated Mechanical Engineering Technologies, 12, S. Bandery str., Lviv, Ukraine, E-mail: serhii.m.pasternak@lpnu.ua, ORCID 0009-0009-6593-3315
[2] Department of Robotics and Integrated Mechanical Engineering Technologies, 12, S. Bandery str., Lviv, Ukraine, E-mail: vadym.v.stupnytskyi@lpnu.ua, ORCID 0000-0002-0921-3980

ANALYSIS AND DEVELOPMENT OF A CUTTING FORCE MEASUREMENT SYSTEM UNDER PRE-HEATING CONDITIONS OF THE WORKPIECE

Received: October 18, 2024 / Revised: November 03, 2024 / Accepted: November 11, 2024

https://doi.org/

Abstract. The issue of determining cutting forces in machining processes is relevant due to the need to improve the efficiency, quality, and accuracy of hard-to-machine materials. In particular, preventive heating of the workpiece can reduce the mechanical resistance of the machined material, which reduces the load on the tool and increases its service life. The article aims to study and analyze the equipment design for measuring cutting forces under conditions of preventive heating. The article discusses the key features of various types of dynamometers, including piezoelectric, strain gauge, mechanical, and hydraulic, which are used to record force effects while processing multiple materials. The advantages and limitations of each dynamometer type are presented, considering specific operating conditions, including temperature, possible deformations, and resistance to mechanical stress. The design features of equipment for studying cutting forces under conditions of preventive heating are described. The article also focuses on the measurement range, a critical parameter when working with different materials. The choice of metrology equipment depends on the workpiece's material, the processing temperature regime, and accuracy requirements. Correct equipment setup and calibration ensure high accuracy and stability of measurements even in difficult conditions, such as preventive heating.

Keywords: cutting force, preheating, strain gauge, dynamometer, thermal strain, stress, cutting load.

Introduction

Measuring cutting forces is one of the critical aspects of quality control and optimization of machining processes. In the industrial sector, the need for reliable and accurate measuring systems that provide real-time data on the load on cutting tools during cutting is constantly growing. This information is needed to improve machining efficiency, reduce tooling costs, and ensure consistent quality of finished products. The forces that occur during cutting significantly impact tool wear, energy consumption, and productivity, so their accurate measurement becomes critical for effective planning of the structure and parameters of machining operations, especially for products with high hardness and thermal resistance.

Modern methods of measuring cutting forces include various dynamometers, from mechanical and hydraulic to electronic systems. Each type of equipment has its characteristics, advantages, and limitations depending on the operating conditions. Among modern solutions, piezoelectric and strain gauge sensors are of particular interest, as they are characterized by high sensitivity and accuracy, simultaneously allowing for the simultaneous measurement of forces in three directions. Such sensors are becoming increasingly popular for research and industrial applications, particularly when processing difficult-to-machine materials such as titanium, chrome-nickel, and other high-alloy superalloys, which are used effectively in the aerospace and energy industries [1, 2].

This article aims to comprehensively analyze existing methods and designs of dynamometers for measuring cutting forces and describes the developed FlexiForce40X dynamometer with strain gauges. The article discusses the principle of operation of the unit and methods of calibration and calibration. It also presents the prospects for using the FlexiForce40X for research on machining materials at high temperatures resulting from preventive heating of the workpiece

Literature Review of Existing Methods and Equipment for Cutting Forces Measurement

Determining cutting forces is critical for quality control and optimization of machining processes. Various types of dynamometers are used in modern research and industrial applications.

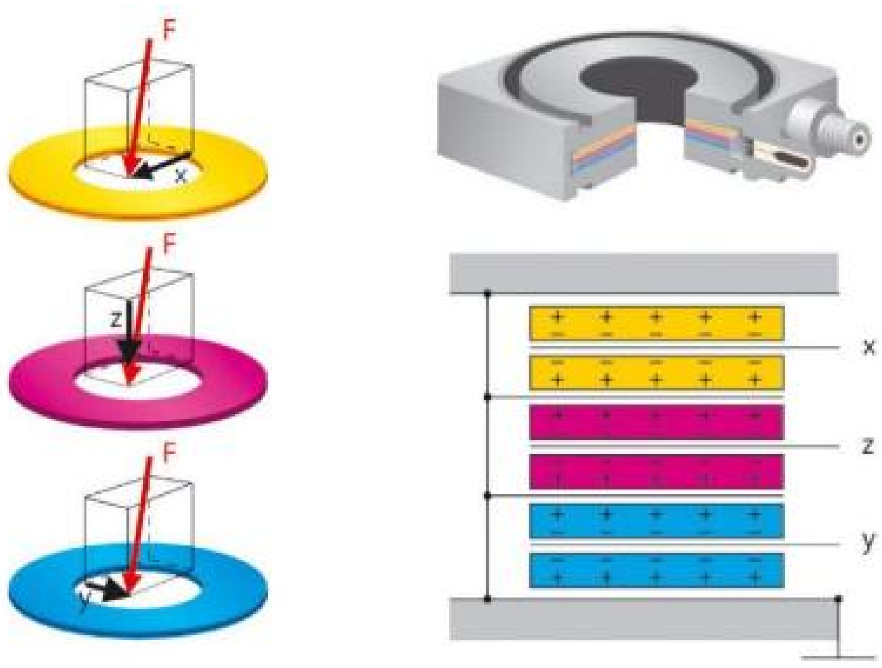

Fig. 1. Design of a piezoelectric dynamometer

One of the most accurate and advanced measurement methods is piezoelectric sensors, which measure forces with high sensitivity and accuracy. The force to be measured is distributed among four 3-component force sensors located between the base and top plates. Each sensor has three pairs of quartz plates, one sensitive to pressure in the *z*-direction and the other two to shear in the *x*- and *y*-directions, respectively (Fig. 1) [3, 4].

Another effective method of measuring cutting forces is to analyze the data obtained by recording changes in electrical resistance in a mechanically loaded system. When the sensor is stressed, its material's slight deformation occurs, measured by strain gauges integrated into the structure. This deformation affects the resistance of the strain gauges, which, in turn, allows us to calculate the applied force (Fig. 2) [5, 6, 7].

There are also other mechanical and hydraulic methods of force measurement. Mechanical dynamometers are the simplest of all types and usually consist of a spring or lever that deforms under the action of an applied force. The main component is a spring or other elastic part that stretches or contracts when a force is used, and a scale shows the amount of force that corresponds to the deformation. A hydraulic device operates based on changes in fluid pressure under the influence of a mechanical load. It consists of a chamber filled with fluid and a piston that deforms under the influence of a force. The chamber is connected to a pressure gauge that measures the fluid pressure. The main advantage of hydraulic dynamometers is their ability to measure large forces. However, their accuracy is usually lower than electronic or piezoelectric dynamometers [1, 2].

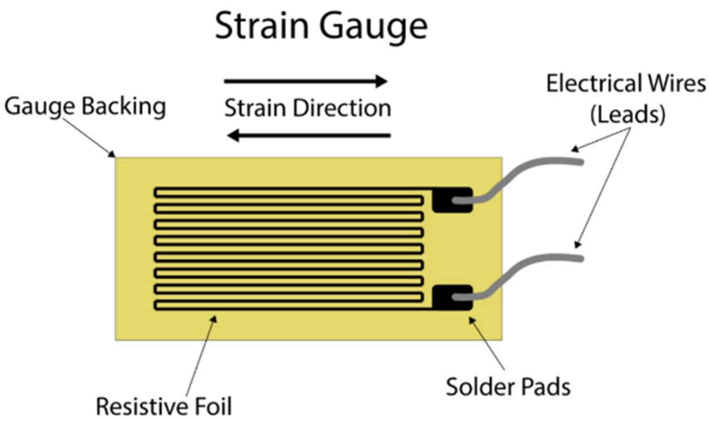

Fig. 2. Schematic diagram of strain gauge operation

The article's primary purpose is a problem-oriented scientific analysis of equipment designs used to determine cutting forces under conditions of preventive heating. Preheating reduces the material resistance during cutting, reducing the load on the tool and increasing its service life. This technology also affects overall machining performance by lowering machining time and energy costs. Preheating is especially important when working with difficult-to-machine materials such as titanium and superalloys, which are widely used in the aerospace and energy industries. These materials are highly durable and resistant to high temperatures and corrosion, making them ideal for specialized applications and much more difficult to machine.

Design Features of Devices for Measuring Cutting Forces Under Conditions of Preventive Heating of the Workpiece

When designing equipment for measuring cutting forces in conditions of preventive heating of workpieces, it is necessary to consider several factors that directly affect the accuracy and reliability of metrology equipment. One of the main aspects is temperature resistance because the workpieces are heated, and the equipment must operate stably without losing measurement accuracy. This is especially important for piezoelectric sensors because they are sensitive to temperature changes. Therefore, cooling or thermal protection systems become integral to the design [3]. Temperature resistance is also critical for strain gauges, as temperature changes can affect the resistance of the materials used to make the strain gauges. Typically, the housings are made of heat-resistant materials for such systems to ensure measurement stability [6].

A similar situation arises with mechanical dynamometers. In them, temperature changes can lead to the deformation of springs or levers, affecting measurements' accuracy. Therefore, for such systems, it is necessary to use heat-resistant alloys or additional heat-insulating materials to avoid the influence of temperature on operation. Hydraulic dynamometers also have their problems – the fluids used in such systems must maintain the stability of their properties at high ambient temperatures. Therefore, only special high-temperature fluids can ensure stable operation of the piston system without the influence of high temperatures.

Measurement accuracy is another crucial aspect of the efficiency and quality of catch measurement. Piezoelectric sensors are susceptible to the slightest change in force, so the equipment design must be as rigid as possible to avoid any deformation or vibration that could distort the results. The situation is similar with strain gauges: the installation of such sensors must be exact, and the design must resist any external influences. The strain gauges should be located where the most significant deformation is expected to occur to ensure a stable signal.

Mechanical dynamometers require careful calculation of the stiffness of springs or levers. If the design is too stiff, measurements of small forces can be inaccurate, while excessive softness can lead to loss of sensitivity under high loads. In hydraulic dynamometers, it is essential to properly size the piston and pressure gauge to avoid errors in pressure measurement, especially when the pressure difference is slight.

Another essential feature is resistance to damage caused by mechanical deformation. This is especially important for force measurement systems for machining materials such as titanium or superalloys, where significant cutting forces are generated [3]. Piezoelectric sensors require a solid base and stable mounting, as even slight deformation can lead to data distortion. Strain gauge sensors must be positioned to allow for possible overload, leaving a certain margin for extreme pressures. Mechanical and hydraulic dynamometers, on the other hand, must be able to withstand peak loads without breaking or deforming, so proper force distribution to all components is critical to maintaining structural integrity.

Any system must undergo calibration and taring procedures before utilization. This procedure is mandatory for all types of dynamometers. During the design process, it is essential to consider the possibility of using reference loads to fine-tune the systems, particularly for piezoelectric and strain gauge systems, where even minor errors can result in significant measurement deviations. When designing equipment for measuring cutting forces under preheating conditions, it is crucial to evaluate the equipment's temperature resistance, accuracy, resistance to mechanical stress, and calibration of the metrology equipment.

The measuring range is another crucial parameter when choosing and using a particular dynamometer type. This concept encompasses the minimum and maximum force values the instrument can accurately record. The operating conditions, workpiece material, tools, and machining environment significantly impact selecting the appropriate measuring range. Selecting the proper measuring range ensures accurate and reliable results. In the context of measuring cutting forces during the machining of heavy materials such as titanium or superalloys, the measuring range must be suitable for the characteristics of the materials and process. For example, when machining chrome-nickel alloy workpieces or other superhard materials, significant cutting forces of up to 1000 N are generated. For softer materials such as aluminum alloys, the cutting forces can be lower in order of magnitude, requiring a different measuring range [8, 9, 10].

Piezoelectric sensors have a wide measuring range and can detect forces from very small to large values. This makes them ideal for dynamic processes where rapid changes in cutting forces can occur. They can measure cutting forces in multiple directions (X, Y, Z), which allows for accurate data on the full force vector. For them, the measurement range must cover both the low forces during the initial machining stages and the peak loads when cutting hard materials. For example, a typical range for such systems can be from a few Newtons to several thousand Newtons, depending on the type of tool and material being machined [3], [4].

Strain gauge systems also have a wide measuring range, although their accuracy at low forces may be less than that of piezoelectric sensors. The measuring range of strain gauges is often customized to specific conditions. This makes them suitable for light-cutting conditions and highly loaded machining, especially at elevated temperatures, typical for machining high-alloy steels or superalloys [5].

Mechanical dynamometers, which work based on spring or lever deformation, usually have a limited measuring range compared to their electronic counterparts. They are suitable for measuring average forces, and the mechanism's accuracy limits their range. Typically, the measuring range of such dynamometers can be more than 2–3 thousand N, but they are not recommended for accurate measurement of small forces. In addition, the accuracy may decrease when operating at high temperatures.

Hydraulic dynamometers can operate under heavy loads, so their measuring range is geared toward high forces. They can measure very high (over 5,000 N) cutting forces, making them suitable for heavy machining of large or hard workpieces. However, the accuracy at low forces can be poor, so hydraulic dynamometers are rarely used for high-precision operations measuring small cutting forces.

Preheating the workpiece during machining also affects the selection of the measuring range. At higher temperatures, the workpiece material can change its mechanical properties, which leads to changes in cutting forces. In this case, the measuring range must consider the changes caused by temperature. Piezoelectric and strain gauge sensors typically have better temperature response, allowing them to operate over a wide range without losing accuracy [8–10].

The choice of measurement range for equipment depends on some factors: material type, processing conditions, temperature conditions, and the characteristics of the measuring devices. Piezoelectric sensors have a wide range and high accuracy, while strain gauge systems are reliable in difficult conditions. Mechanical and hydraulic dynamometers are limited but useful for measuring large forces. Choosing the proper range will ensure accurate and reliable measurements when processing difficult-to-machine materials.

Description of the Design of the Dynamometer FlexiForce40X

The author has developed a dynamometer for measuring cutting forces under conditions of preventive heating of the workpiece, based on a mechanical system that includes a main fixed carrier frame 1, which is fixed on the lathe toolholder, load cells for fixing force effects 4, a movable block two and a cutting tool 3 (Fig. 3). Software based on the Arduino platform was developed to control the process of data collection and processing, and a corresponding calibration system for calibrating the measuring system.

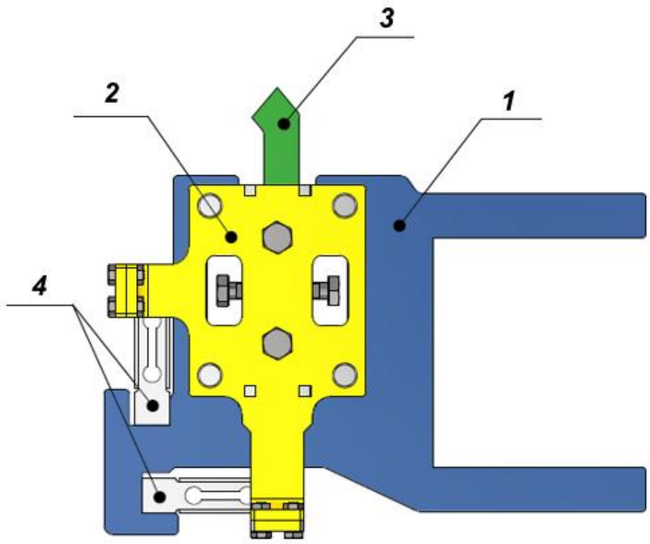

Fig. 3. Schematic diagram of the dynamometer FlexiForce40X

The main structural elements of the dynamometer provide the following functions (Fig. 3):

1. The main bearing frame is the base that provides rigidity and stability of the entire metrological system. It supports fixing other components of the dynamometer. The strength and stability of this part minimize vibrations and deformations during the measurement, which is critical to ensuring measurement accuracy.

2. The movable unit is an element attached to the main support frame by damping bushings. This mounting system allows the block to move slightly under the influence of applied loads, ensuring equivalent force transmission to the load cells while reducing the impact of vibrations and sharp shocks. The soft bushings act as dampers that mitigate mechanical impacts and protect both the sensors and the entire structure from excessive deformation, increasing the reliability and durability of the dynamometer.

3. A cutter is a cutting tool that directly interacts with the workpiece during the cutting process. The force applied to the cutter is transmitted through the movable block and the mounting system to the load cells.

4. Load cells are a crucial element of the measuring system. This design uses strain gauges with a measuring range of up to 1000 N. These sensors are installed where the most significant deformation is expected during cutting, allowing for accurate force load readings. The strain gauges work on the principle of strain measurement: the cutting force causes deformation of the material on which the strain gauges are mounted, which changes their resistance. These resistance changes are converted into an electrical signal sent to the controller.

Fig. 4. Equipment in operation

Method of Measuring Cutting Force with the Dynamometer FlexiForce40X

A strain gauge typically comprises a thin metal or semiconductor strip mounted on a dielectric substrate. This strip is the main sensing part that changes its properties under the influence of external forces. Metal strain gauges are made of special alloys, such as constantan or manganese, which provide high parameter stability. Semiconductor load cells have a higher sensitivity, but their resistance changes nonlinearly, which makes signal processing more difficult. The strain gauge principle is based on the effect of strain resistance – a change in electrical resistance under the influence of mechanical stress. When a force is applied to the strain gauge, its structure deforms, which leads to a change in its resistance. This change in resistance can be measured using an electrical signal, which allows you to conclude the degree of deformation of the material on which the strain gauge is installed.

The strain gauge used in the developed dynamometer is a high-precision measuring element designed to determine force by measuring deformation. The main technical characteristics of this load cell include a maximum load of 1 to 1000 N and an accuracy class of C3. The sensor has a protection level (IP65), making it suitable for harsh environments. The load cell material is aluminum, which provides lightweight construction and corrosion resistance. This strain gauge has low errors such as hysteresis and creep, making it suitable for high-precision measurements.

This part of the article presents the basic calculation formulas used to determine the strain, applied force, and stress based on the data received from the load cell. The conversion of an analog electrical to a digital signal for further data processing is also described. The sequence of these actions is as follows.

1. *Calculating strain with a load cell*

The following formula can be used to determine the mechanical strain of a material under the influence of an applied force:

$$\varepsilon = \frac{\Delta R}{R_0} \cdot \frac{1}{GF}, \tag{1}$$

where ΔR is the change in strain gauge resistance under deformation; R_0 is the initial strain gauge resistance; *GF* is the Gauge Factor (strain gauge sensitivity, which is the proportionality coefficient between strain and resistance change).

This formula allows you to obtain the value of mechanical strain by measuring the change in strain gauge resistance. The strain gauge sensitivity (*GF*) is an important parameter that considers the sensor's sensitivity to changes in mechanical strain.

2. *Calculation of the applied force*

Given a measured strain value ε, the applied force can be calculated using the formula:

$$F=E\cdot A\cdot\varepsilon, \quad (2)$$

where E is the Young's modulus of the material, characterizing its elastic properties; A is the cross-sectional area of the sample; ε is the measured strain.

This relationship allows you to determine the force applied to the sample that caused the deformation. Calculating the force is essential in analyzing the cutting force, especially under preventive heating conditions when the material becomes more susceptible to deformation.

3. *Stress calculation*

The stress in a material can be determined using Young's modulus and a predefined strain value:

$$\sigma = E \cdot \varepsilon, \quad (3)$$

where σ is the stress occurring in the machined material, E is Young's modulus, and ε is the measured strain.

4. *Converting an electrical signal*

To analyze changes in resistance, you can convert an electrical signal to voltage. This is done using the following formula:

$$V_{out} = \left(\frac{\Delta R}{R_0}\right) \cdot V_{in}, \quad (4)$$

where V_{out} is the output voltage corresponding to the change in resistance; ΔR is the change in resistance of the strain gauge; R_0 is the initial resistance of the strain gauge; V_{in} is the input voltage.

Arduino-based software is used to collect and process data from load cells. Arduino is an open platform for developing electronic devices that allows you to easily connect sensors and work with them using special program code. Arduino in this system performs the following functions:

– reading data from load cells connected to the board's analog or digital inputs.

– signals are processed and converted into numerical cutting force values.

– displaying the results on the screen or transferring the data to a computer for further analysis.

Using Arduino provides considerable flexibility in customizing the system for different types of operations and materials. With the appropriate settings and code, you can quickly adapt the dynamometer to measure different ranges of cutting forces and adjust the required parameters.

Dynamometer calibration calibrates a measuring system to eliminate possible errors and ensure measurement accuracy. To do this, known reference loads are applied to the structure, then the load cells' readings are recorded.

Calibration takes place in several stages:

1. Prepare a reference load. This is usually done using calibrated weights or springs with accurate force values. For example, you can use standard weight samples to generate a load corresponding to the dynamometer's measuring range.

2. Connect the system to the Arduino. The load cells are connected to the controller, and the Arduino program reads the initial force values. The software adjusts the coefficients if they do not correspond to the reference load.

3. Calibration. After applying different loads, the system is adjusted so that the deviations between the reference and measured values are minimal. This eliminates any inaccuracies in the operation of the load cells and the system.

4. Final testing. After calibration, the dynamometer is tested for measurement accuracy under various loads. If the results meet the expectations, the system is considered ready for operation.

The taring method ensures accurate measurements, especially when working with high-cutting resistance materials. This dynamometer system with 400 N load cells and Arduino-based software provides high accuracy and flexibility in measuring cutting forces under preheating conditions. The design offers high rigidity and resistance to temperature and mechanical stress, which makes it reliable and efficient in industrial environments. Calibration and proper system setup guarantee measurement accuracy, an important factor in achieving high-quality material machining.

The Main Advantages and Prospects of Using the Measuring Device FlexiForce40X

The FlexiForce40X has excellent potential due to its cost-effectiveness, flexibility, ease of setup, and adaptability to different applications. Compared to similar devices, such as piezoelectric, hydraulic, and mechanical dynamometers, it is characterized by low cost and ease of maintenance. This makes it an attractive solution for manufacturing plants, research laboratories, and engineering institutions.

Main advantages:

1. *Cost-effectiveness*. While providing highly accurate force measurement, traditional piezoelectric and hydraulic dynamometers are often significantly more expensive due to their complex design and high maintenance requirements. Compared to them, this setup is more cost-effective because it uses more straightforward and more affordable components such as load cells and Arduino-based electronics. This reduces production and maintenance costs, a significant advantage for small and medium-sized enterprises.

2. *Flexibility of settings*. Using the Arduino platform gives a significant advantage in customizing and adapting the system for specific needs. The setup allows you to easily change measurement parameters, update firmware, and add new features without changing the hardware. This makes the system extremely versatile, allowing it to measure cutting forces and other types of mechanical loads. Arduino supports a large number of peripherals and sensors, which will enable you to expand the functionality of the system further. For example, you can connect temperature sensors, vibration sensors, or other types of load cells for a more detailed analysis of the material machining process.

3. *Compactness and simplicity of usage*. Another significant advantage is the compact design. In contrast to hydraulic dynamometers, which require large fluid tanks and complex pumps, your unit is much more compact and lightweight. This makes it ideal for use in tight spaces or on small production floors. The ease of assembly and disassembly also makes it an advantage when quickly reconfiguring or moving equipment to another site.

4. *Measurement accuracy*. Despite the low cost, the dynamometer provides fairly high accuracy in measuring measurements due to modern load cells. The strain gauges used in the system measure the deformation that occurs under the action of applied forces. This makes it possible to obtain the precise readings necessary to control the quality of material processing processes, such as turning or milling.

5. *Low maintenance costs*. The system does not require expensive components for maintenance. Since the system is based on electronic components, maintenance is limited to periodic calibration and, if necessary, replacement of sensors or electronic modules. Compared to hydraulic systems, which may require regular fluid checks and replacement of seals or other mechanical parts, this significantly reduces costs.

The setup can be used to measure cutting forces and determine other types of mechanical loads. For example, it can be adapted to measure loads in milling machines and presses or even to test materials for tension or compression. These tasks can be realized by properly configuring the sensors and firmware on the Arduino platform.

In addition, integrating with other devices opens up new prospects for automating and monitoring production processes. The system can be connected to a shared network of sensors and controllers, allowing real-time monitoring of production processes and making corrections if necessary. This is especially important in modern production systems, where more and more attention is paid to automation and precise parameter control.

Thus, the developed dynamometer has excellent potential for use in various industries due to its affordability, flexibility, and reliability. It is an excellent solution for small and medium-sized enterprises looking for effective ways to control force loads without investing heavily in expensive systems.

Conclusions

1. The measurement of cutting forces is an essential element in optimizing the machining of materials, which ensures high-quality machining and reduces production costs. This study analyzed methods and equipment for measuring cutting forces, including mechanical, hydraulic, strain gauge, and piezoelectric dynamometers. The piezoelectric and strain gauge systems proved to be the most accurate for machining difficult-to-machine materials.

2. The developed FlexiForce40X dynamometer on the Arduino platform demonstrates the effectiveness of measuring cutting forces, even in conditions of preventive heating of workpieces. Thanks to the flexibility of the Arduino platform settings, the FlexiForce40X can be adapted to different measurement ranges, making it economically attractive for laboratory research and small businesses.

3. The FlexiForce40X can be integrated into automated control systems, allowing real-time monitoring of cutting parameters, which is especially important for modern manufacturing. In addition, its compact size, low maintenance, and flexibility will enable the machine to be adapted to different machining environments. This reliable, cost-effective device can improve machining quality, extend tool life, and reduce energy costs. Using such a dynamometer will contribute to developing automated control systems and open up new opportunities for machining complex materials in the aerospace and energy industries.

References

[1]. D. A. Stephenson, and J. S. Agapiou, "*Metal Cutting Theory and Practice*", Third Edition, CRC Press, 947 p., 2018. DOI: 10.1201/9781315373119.

[2]. H. A. Kishawy, and A. Hosseini, *Machining Difficult-to-Cut Materials*, Cham: Springer International Publishing, 2019. DOI: 10.1007/978-3-319-95966-5

[3]. https://www.kistler.com/INT/en/c/force-sensors/CG21-force-sensors/ Piezoelectric force sensors.

[4]. https://www.pcb.com/ Force Sensors for Research & Development

[5]. A. Khairul, end Yohanes, "Rancang bangun dinamometer berbasiskan strain gauge dengan batang sensor tipe four square stalk untuk pengukuran gaya potong mesin bubut", *Jurnal Online Mahasiswa Fakultas Teknik Universitas Riau*, vol. 3, No. 2, pp. 1–7, 2016.

[6]. U. Şeker, A. Kurt, and İ. Çiftçi, "Design and construction of a dynamometer for measurement of cutting forces during machining with linear motion", *Materials & Design*, vol. 23, No. 4, pp. 355–360, 2002. DOI: 10.1016/s0261-3069(02)00013-4

[7]. S. Yaldız, and F. Ünsaçar, "A dynamometer design for measurement the cutting forces on turning", *Measurement*, vol. 39, No. 1, pp. 80–89, 2006. DOI: 10.1016/j.measurement.2005.07.008

[8]. R. Muhammad, "Hot Ultrasonically Assisted Turning of Ti-15V3Al3Cr3Sn: Experimental and Numerical Analysis", *PhD Thesis*, Loughborough University, 2013.

[9]. B. Maher, V. Wagner, G. Dessein, J. Sallabery, and D. Lallement, "An Experimental Investigation of Hot Machining with Induction to Improve Ti-5553 Machinability", *Applied Mechanics and Materials*, vol. 62, pp. 67–76, 2011. DOI: 10.4028/www.scientific.net/AMM.62.67

[10]. A. K. Parida, end K. Maity, "Comparison the machinability of Inconel 718, Inconel 625 and Monel 400 in hot turning operation". *Engineering Science and Technology, an International Journal*, vol. 21, No. 3, pp. 364–370, 2018. DOI: 10.1016/j.jestch.2018.03.018

[11]. R. Muhammad, N. Ahmed, H. Ullah, A. Roy, end V. V. Silberschmidt, "Hybrid machining process: experimental and numerical analysis of hot ultrasonically assisted turning", *The International Journal of Advanced Manufacturing Technology*, vol. 97, pp. 2173–2192, 2018. DOI: 10.1007/s00170-018-2087-6

[12]. C. Wang, R. Rakowski, K. Cheng, "Design and analysis of a piezoelectric film embedded smart cutting tool", Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, vol. 227, No. 2, pp. 254–260, 2013. DOI: 10.1177/0954405412462785

[13]. N. Vorkapić, B. Kokotović, "Synthesis and analysis of the tool dynamometer for turning operations", *in: Proceedings of the 13th international scientific conference MMA 2018 – flexible technologies*, Novi Sad, Serbia 28–29 september 2018, University of Novi Sad-Faculty of Technical Sciences, pp. 99–102, 2018.

[14]. X. Chen, K. Cheng, end C. Wang, "Design of a smart turning tool with application to in-process cutting force measurement in ultraprecision and micro cutting", *Manufacturing Letters*, vol. 2, No. 4, pp. 112–117, 2014. DOI: 10.1016/j.mfglet.2014.07.001

[15]. M. Sadílek, J. Dubský, Z. Sadílková, end Z. Poruba, "Cutting forces during turning with variable depth of cut", *Perspectives in Science*, vol. 7, pp. 357–363, 2016. DOI: 10.1016/j.pisc.2015.11.055

[16]. K. Venkatesan, K. Manivannan, S. Devendiran, A. T. Mathew, N. M. Ghazaly, Aadhavan, S. M. Neha Benny, "Study of forces, surface finish and chip morphology on machining of inconel 825", *Procedia Manufacturing*, vol. 30, pp. 611–618, 2019. DOI: 10.1016/j.promfg.2019.02.086