Method and System for Measuring the Cutting Torque and Feed Force used for Hole Processing

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Abstract: The introduction of new materials in the cutting processes generates the need for supplementing existing knowledge with new data specific to these materials. By monitoring the machining parameters, information through which these can be optimized is obtained. The aim of the paper is highlighted by the author's concern for the development of a system for measuring the feed forces and cutting torques for research and educational activities. The proposed measurement system is developed for drilling processes. In this paper, the components of the equipment and their func-tions are presented. The research method is the experimental one. The final part of this research presents some demonstrative tests meant to exemplify the capability of the system, as well as the conclusions drawn and the personal point of view which highlights new fields of research.

Keywords: feed force; cutting torque; drilling; data acquisition; measurement; equipment development

1 Introduction

The machining of plastics has specific features [1, 2]. Within the framework of experiments carried out by several researchers in the field of hole machining [3-5], the influence of the machining parameter on the quality of surfaces and dimensional accuracy was studied [6-8]. For in-depth knowledge of the process, the monitoring of cutting torque [9-11] and feed force [12-14] would be useful. By monitoring the cutting torque and feed force we will be able to get a more comprehensive picture of the phenomena that occur in the area of chip removal [15-17].

The aim of the work is to develop low-cost research equipment with high measurement accuracy. The equipment is developed for the study of the cutting process (cutting torque and feed force) with twist drills in industrial plastics. This study is needed because the behaviors of plastics is very different from that of metals when they are being cut. Small changes in the drill – cutting parameters assembly have major effects on the quality of the machined hole [18].

By creating certain equipment or a device for measuring the cutting torque and feed force, research and publication opportunities will be created, such as:

- The influence of low temperatures on the accuracy of machining and on the quality of the processed surface in the case of industrial plastics;
- Dimensional accuracy of holes processed in industrial plastics;
- The influence of cutting speed when machining the thread with the tap on the resistance of the thread;
- Study of the process of the internal thread forming with thread forming taps;
- Study of threaded metal insertions mounted in parts made of industrial plastic and aluminum.

During the development of the equipment, the main criterion was its execution incurring minimum expenses. There exists equipment for monitoring cutting parameters, and an interest on the researchers' part in the development of such equipment can be seen. Recently, various simple or complex systems have been developed for measuring feed forces and cutting torque.

In educational systems, cost related aspects when ensuring the logistical aspects required for the experiments to be carried out with the involvement of the students at bachelor, master and doctoral level are fundamental. When developing a method and a specific piece of equipment, the directions of experimental research in which the local academic environment is involved and wants to develop were analyzed. Said development is hampered or blocked by the high costs incurred by the purchasing of measuring equipment.

By implementing the method and the equipment proposed in this research, the quality of the experiments, carried out with the students will increase. It becomes possible to present and repeat experiments on the basis of which students become familiar with various aspects related to the machining of materials, the influences of the machining parameters and processing conditions on the accuracy and quality of the surfaces resulting from the processing.

The purpose of developing the measurement system and method leads to:

- The possibility of carrying out demonstrations within the framework of teaching activities, and
- The building of the applied research facilities.

2 State of Art on the Characteristics of Existing Dynamometers

Studying the technical data of the equipment offered for sale or developed by the research teams, I made a synthesis of the measurable cutting moments, Table 1.

In the paper I present an equipment developed for measuring the cutting torque in the range 0-0.5 Nm respectively 0-40 Nm to study the processing of holes in plastics by cutting. With this equipment I focus my studies on holes with diameters in the range 0-24 mm.

Table 1
Synthesis of existing dynamometers

No.	Equipment	Cutting torque [Nm]	References
1	Kistler 9272 (plate dynamometer)	–200 ... 200	[19]
2	Kistler 9170A (rotating dynamometer)	–150 ... 150	[19]
3	Kistler 9171A (rotating dynamometer)	–1 000 ... 1 000	[19]
4	Kistler 9109AA - MicroDin (plate dynamometer)	-50 … 50	[22]
5	Research device 1 (rotating dynamometer)	0 ... 160	[16]
6	Research device 2 (rotating dynamometer)	0 ... 30	[20]
8	Research device 3 (rotating dynamometer)	0 ... 40	[21]
9	Research device 4 (rotating dynamometer)	0 ... 10	[15]
10	Developed device v1 (plate device)	0 ... 0.5 (0 ... 1)	Present paper
11	Developed device v2 (plate device)	0 ... 20 (0 ... 40)	Present paper

The identified measuring devices and equipment partially cover the measuring range 0-10 Nm and the hole diameter 0-24 mm, the field in which the cutting torque we want to study.

Through the designed equipment, I complete this gap and create the facility to re-search with a high accuracy the moments that appear when processing the holes with the diameter in the range 0-24 mm.

Through these measurements (with a high accuracy) we propose the analysis the cutting torque and his influence on processing precision and the quality of the obtained surface.

3 System and Method for Measuring Cutting Torque and Feed Force when Processing Holes

The proposed method and working principle aim is to highlight the influence of machining parameters on the feed force and the cutting torque on drilling.

The requirements imposed on the drafting and design of the measurement system and method were:

- real time measurement of the feed force and the cutting torque when machining holes and internal threads;
- graphical visualization of the variation of the feed force and of the torque during processing;
- the acquisition of data regarding feed force and cutting torque during processing in order to further analyze the experimentally collected data.

The objectives pursued by achieving the measurement system and method:

- real time measurement and visualization of the feed force and/or cutting torque when processing hole type internal surfaces of rotation and internal threads;
- acquisition of data regarding feed force and cutting torque;
- processing and reading the experimental data resulting from measuring the feed force and cutting torque;
- visualization of phenomena during machining through their influence on the cutting torque and feed force;
- studying the feed force, cutting torque and their effects on the following machining processes:
    - Drilling;
    - Thread tapping;
    - Thread forming;
    - Reaming.
- the behavior of different plastics when processing them through machining;
- studying the influence of cutting tool geometry on the feed force and cutting torque;
- studying the surface quality depending on machining parameters and the phenomena identified during processing;
- determining the influence of low temperature on the feed force and the surface quality resulting from processing.

4 Operation Principle of the Proposed Measuring System

During the machining, the twist drill type cutting tool is stressed by a cutting torque and a feed force. Some of the measuring solutions of the torque and force values are oriented to their determination with equipment fixed on the cutting tool. The force and torque, which stress the cutting tool, will also stress the semi-finished product, except it will do so in the opposite direction.

In the case of the proposed solution (Figure 1), the force and the torque will be measured with the help of certain measuring equipment having also the function of fixing the semi-finished product to the machine tool. The cutting tool is fixed in the machine tool spindle with dedicated tool holders.

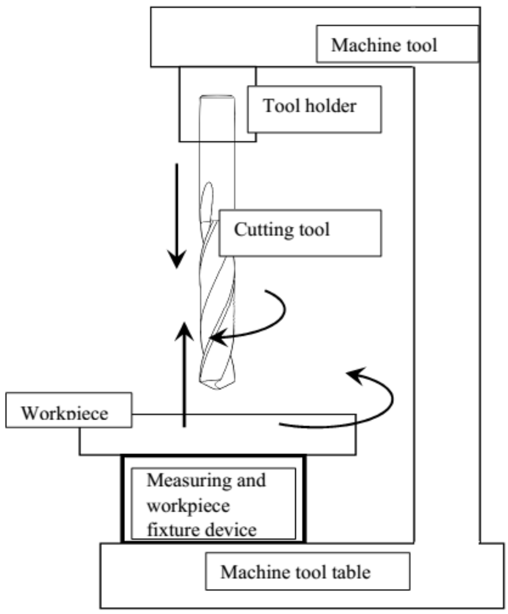

Figure 1
Essential connections

5 The Structure of the Measuring Device

The measuring device has been developed in a modular structure so that it is easy to use in research.

As a component it consists of a "3" base plate on which the other subassemblies are mounted, depending on the application for which the system is used.

Figures 2, 3 and 4 and Table 2 show the component parts of the system depending on the measurement objectives.

Table 2
Components of the measuring system

No.	Designation	Comments
1	Dynamometer A	(used to measure the force component of the cutting torque)
2	Support of dynamometer A	
3	Base plate	
4	Test item fixture device	
5	Torque module	
6	Spacer for dynamometer support A	
7	Dynamometer B (external sensor)	(used for measuring the feed force)
8	Assembly of thermal insulation elements	(used in case of cryo-cutting type experiments)

5.1 How to Assemble the Measuring System Depending on the Measurement Objectives

Case 1. At measuring the cutting torque (Figure 2), the equipment will be configured as follows:

On the "base plate" 3 using the "support" 2 the "dynamometer A" marked 1 will be fixed. Also on the "base plate" 3 the ensemble 5 "torque module" is fixed, on which the element 4 "test item fixing device" is mounted.

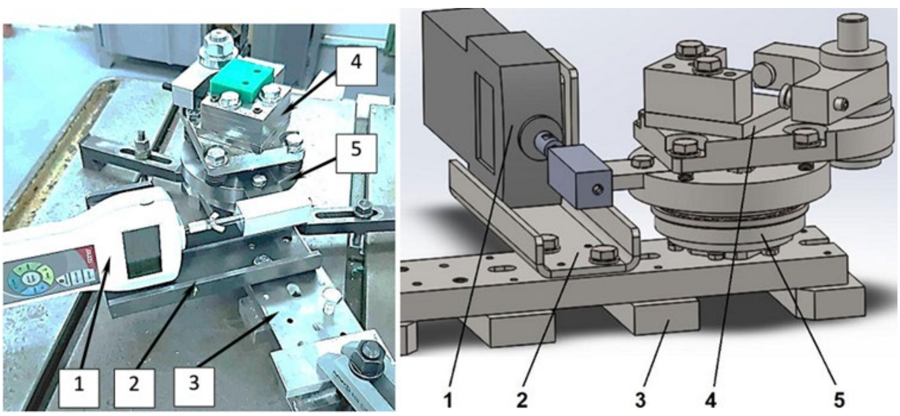

Figure 2
Assembled measuring device for torque measurements

After this, the measuring rod of the dynamometer is coupled with the arm of the torque module.

The ensemble thus made is placed, centered and fixed on the table of the drilling or milling machine tool.

Case 2. In case one desires to measure both the torque and the feed force (Fig. 3), ele-ments 6 "spacer" and 7 "dynamometer B" will also appear in the structure of the said equipment.

When assembling the measuring system, between the base plate "3" and the torque module "5", the element 7 "External sensor of Dynamometer B" is mounted.

By adding the "External sensor of Dynamometer B" 7 the feed force can be measured. The position of the torque module 5 towards the base plate 3 being modified in its turn, the dynamometer A 1 will also be repositioned by mounting a spacer 6 between the base plate 3 and the support 2. The height of the spacer is equal to the height of the external sensor of the dynamometer B.

Case 3. Research at low temperatures

In this case, between the torque module 5 and the test item fixture device 4, an en-semble of parts with the role of thermal insulation is introduced. It is also on the thermal insulation elements that the tray with the cryogenic agent for the cooling of test item is mounted. For these experiments, the test item fixture device will also be cooled.

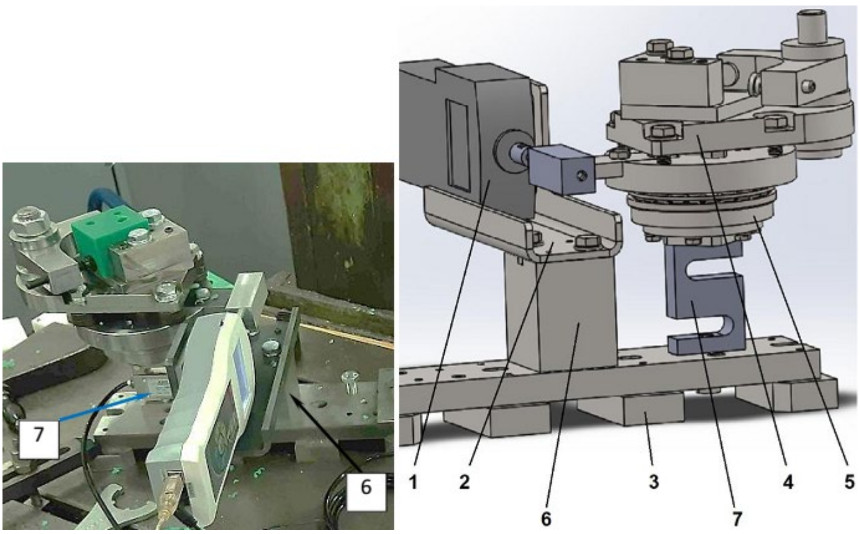

Figure 3
Assembled measuring device for torque and feed force measurements

5.2 Test Specimen

Within the framework of the experiments performed using the proposed and implemented measuring system and method, rectangular parallelepiped test specimens shall be used.

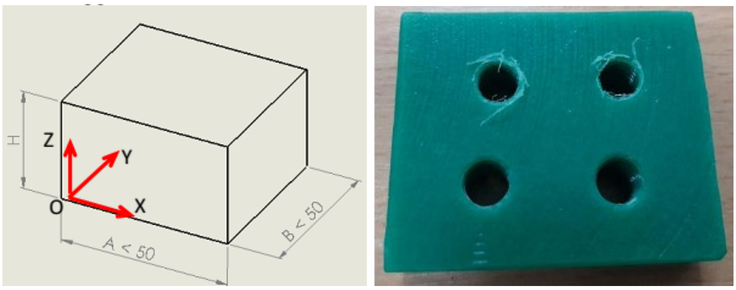

Figure 4
Test specimen

The test specimen fixture device was made so that it could fix the test specimen with the side of the base (A and B) measuring less than or being equal to 50 mm. The height of the test item (H) will be chosen depending on the depth of the hole that is being processed.

5.3 Test Specimen Fixture Device

The device, by its construction, will ensure the same positioning origin for all the pieces from the experimental lots. The origin and axes of the device are the same (Figure 5) as the origin and axes of the test specimen (Figure 4). By rotating the rectangular parallelepiped test specimen, each corner of it can be an origin for each machined hole. This aspect is important, especially when processing the threads, because first the holes can be processed with a twist drill in each test specimen, and then one changes the twist drill and the tool holder of the twist drill with the tool holder with tap collet in which the tap for the experiment is fixed.

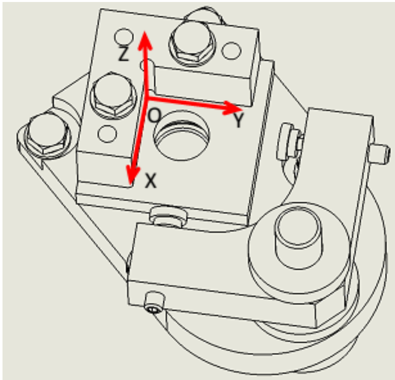

Figure 5
Test specimen fixture device

5.4 Torque Module

The torque module 5 is a set of parts consisting of circular plates of special configurations (5.1, 5.2, 5.5), centered together by means of two bearings (one radial 5.3 and one axial 5.4) so that they rotate smoothly in relation to each other.

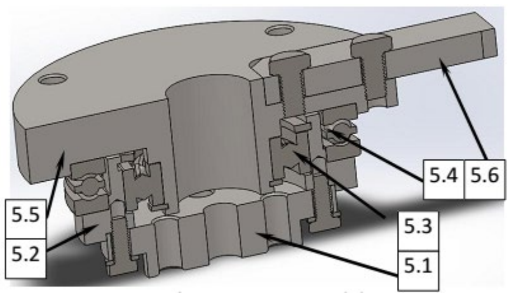

Figure 6
Torque module

The arm 5.6 of the torque module rests on the rod of the dynamometer A (marked with 1, in Figure 2) in order to measure the force component of the cutting torque. Knowing the length of the arm and the force at the end of the arm, the torque can be determined.

The measuring device was designed with two arms 5.6 of different lengths in order to increase the measuring field of the cutting torques. This is why two sets of holes for fixing the support 2, of the dynamometer A, are machined on the base plate 3.

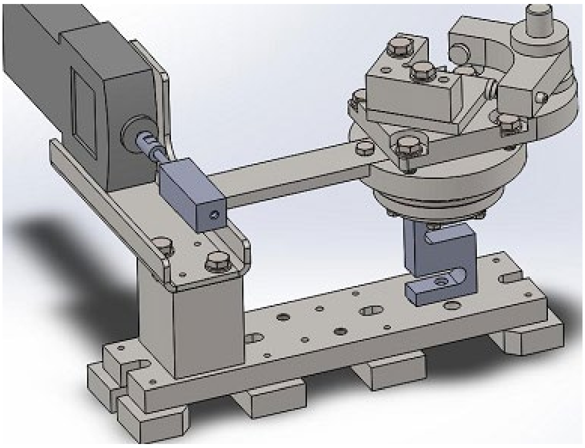

Figure 7
Measuring device in the version with arm of 200 mm

5.5 Measuring Accuracy

Considering that dynamometer A can measure forces up to 200 N, depending on the size of the cutting torque predicted for measurement, the arm of 100 mm or the arm of 200 mm will be used.

With the device equipped with arm of L1=100 mm, it will be possible to measure the cutting torque in the range 0-20 Nm. According to Figure 8 and knowing that the maxi-mum force which can be measured with the dynamometer A (FB200) is 200 N, it is possible to determine the maximum torque that can be measured according to relation 1, as well as the accuracy of this measurement (relation 2).

Measured value: 200 N x 0.1 m = 20 Nm (1)

Measuring accuracy: 0.05 N x 0.1 m = 0.005 Nm (2)

Where:

200 N - the maximum force that can be measured with dynamometer A (FB200)

0.05 N – measuring accuracy of the dynamometer A (FB200).

0.1 m – the length of the arm of the torque module 5

In the case of a 5 N dynamometer (FB5 dynamometer) with a measuring accuracy of 0.001 N according to those presented above, we will be able to measure the cutting torque in the range 0-0.5 Nm with a measuring accuracy of 0.0001 Nm.

With the device equipped with an arm of L2=200 mm and 200 N dynamometer, it will be possible to measure the cutting torque in the range 0-40 Nm.

The calculation of the maximum measuring torque and its measuring accuracy are determined by relations 3 and 4. In case of 5 N dynamometer the measuring range are 0-1 Nm.

Measured value: 200 N x 0.2 m = 40 Nm (3)

Measuring accuracy: 0.05 N x 0.2 m = 0.01 Nm (4)

Where:

200 N - the maximum force that can be measured with dynamometer A (FB200)

0.05 N - measuring accuracy of the dynamometer A (FB200).

0.2 m – the length of the arm of the torque module 5

Using torque arms below 1 m (the length of the arm of the force resulting from the cutting torque being 0.1 and 0.2 m respectively) the measuring accuracy of the cutting torque will be:

- 5 times higher for the torque module with arm L=0.2 m and

- 10 times higher at the torque module with arm L=0.1 m than the measuring accuracy of the dynamometer used.

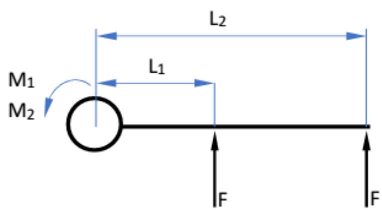

Figure 8

Scaling of measuring accuracy

5.6 The Need of a Correction Coefficient of the Measuring System

During the design phase the frictional forces that appear in the bearings were considered zero because, depending on the bearing manufacturer and its mounting conditions, they will have different values.

After making the equipment, the chosen solution was to experimentally determine the correction coefficient applied to the cutting torque calculated with the formula: the force measured with the dynamometer A x the length of the arm of the torque module.

Thus, I recommend checking the correction coefficient through measurements before each mounting of the equipment and its positioning on the machine tool on which the experiments will be carried out. At the same time, I can conclude that each piece of equipment must be calibrated with its own correction coefficient.

5.7 Determination of the Correction Coefficient of the Measuring System

To determine the correction coefficient a torque screwdriver is used. In this case, we used a Proxxon MicroClick MC5 torque screwdriver with a measuring range of 1-5 Nm and according to the ”Certification of Conformity” with a measurement error of 0,03 Nm, with uncertainty of 0,13

The technological ensemble used to determine the correction coefficient is shown in Figure 9.

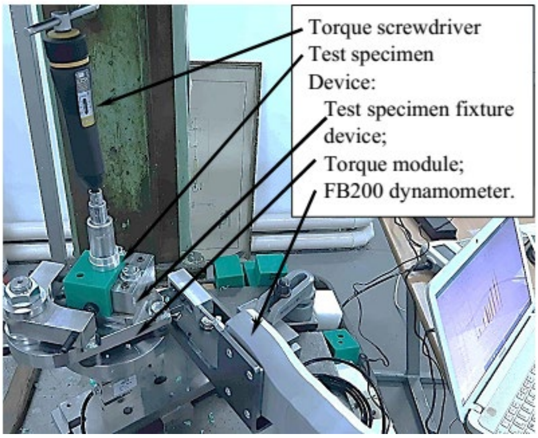

Figure 9
Determination of the correction coefficient

On the torque screwdriver each value of the known torque indicated in the "Certification of Conformity" was adjusted successively, and the device was actuated by the test item element so that the dynamometer record the value of the force component of the torque. The correction coefficient k is defined (formula 5) by the ratio between the test torque (torque set on the torque screwdriver) and the torque determined with the developed equipment (calculated from the force measured by the dynamometer and the arm length).

$$k = \frac{a}{b} \qquad (5)$$

Where:

- torque adjusted on the torque screwdriver
- torque determined with de developed equipment (force x arm).

In Table 3, I centralized the measured data and the calculated coefficients. Figure 10 shows the graph of variation of the coefficient calculated according to the torque set on the torque screwdriver.

Table 3
Measured data and the calculated coefficient

Torque screwdriver MC5	Developed equipment			Correction coefficient	
Adjusted torque	Measured force	Arm of force (construc ive)	Determined torque		Average
a			b	ki	k
[1]	[2]	[3]	[4] = [2x3]	[5] = [1 / 4]	[6]
Nm	N	m	Nm		
1.01	9.65	0.1	0.965	1.046	
3.1	29.45	0.1	2.945	1.052	1,05
5.28	50.25	0.1	5.025	1.050	

Obs.

- The values of the torque in the column [1] are values certified by the metrological bulletin.

- The coefficient k is obtained as the arithmetic average of the coefficients determined in column [5]

Based on the experimental data presented in Figure 9 and Table 3 in this case a correction coefficient of 1.05 will be used within the framework of experiments performed with the proposed system.

When using the arm L2=200 mm of the torque module, the determination of the correction coefficient is determined analogously to the method presented.

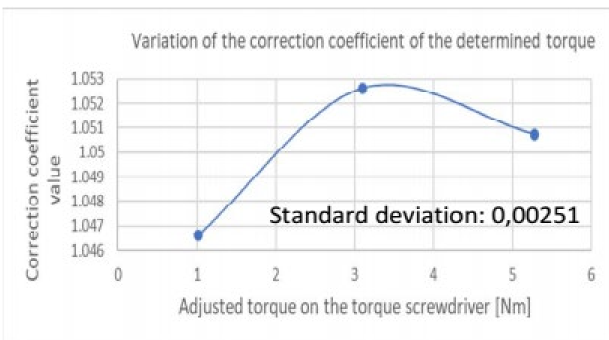

Figure 10
Variation of the torque correction coefficient

6 Applications with the Method and System Proposed for Measuring the Cutting Torque and the Feed Forces used in Hole Processing

To demonstrate the capability of the method and the system proposed and subsequently performed, several experiments are presented, as well as the working technique, the obtaining of the experimental data and some fields of experimental research for which the system will be used.

The presented experiment is the measurement of cutting torque and the feed force when machining holes with a twist drill.

It is our wish to highlight:

- the need for research in the field of new materials for which there is no research data (plastics, composite materials, etc.)
- the aim to reduce research costs
- the aim to support experimental research and education.

6.1 Experiment: Measuring the Cutting Torque and the Feed Force in Hole Processing with the Twist Drill

Within the framework of the experiment, I present the mode of operation for measuring the feed force and cutting torque for processing a hole with a diameter of Ø 6.9 mm, with a twist drill of general use HSS-R ISO 235 (DIN 338), on a universal drilling machine, at a spindle speed of 550 rot/min and a feed of 0.10 mm/rot. Processed material PA6.

6.1.1 Phase 1. Aligning the Equipment with the Machine Tool Spindle

The measuring device is placed on the table of the drilling machine, and the spindle of the torque module is aligned with the axis of the main spindle of the drilling machine.

The alignment of the axis of the measuring system and of the drilling machine (implicitly also of the cutting tool in the current situation of the drill) is important because the coaxially errors will negatively influence the accuracy of the measured values of the cutting torque.

The alignment is achieved by fixing a dedicated centering device in the drilling machine spindle, preferably with a meter with dial, the feeler of which will come into contact with the bore in the test item fixture device. (From the constructive viewpoint), since the assembly phase the concentricity and coaxiality between the bore in the tool holder and the bore of the torque module is ensured.)

The device is fixed on the table of the drilling machine with some clamps.

The dynamometers are connected to the computer on which the experimental data obtained will be recorded and saved. AxisFM data acquisition software is launched for each dynamometer.

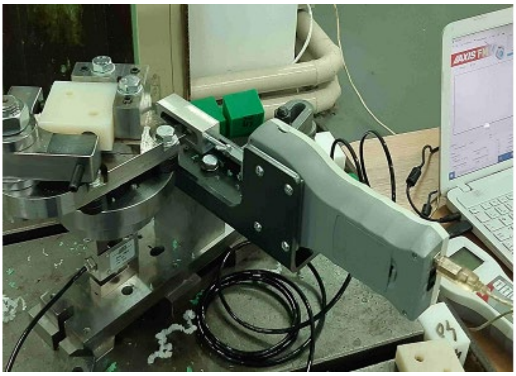

Figure 11
Phase 1. Alignment of equipment according to the axis of the machine tool

6.1.2 Phase 2. Equipment Calibration

At this stage, the proper operation of the dynamometers is checked and the correction coefficient of the measured cutting torque is established.

The dynamometer is calibrated for measuring the feed force:

- reset the dynamometer in this way the mass of the torque module, the mass of the test item fixture device, and the mass of the test item are eliminated.
- place weights with the known mass on the test item fixture device and compare the mass of the weight with the value indicated by the dynamometer.
- determine the correction coefficient of the measured torque.

Follow the steps already described in the chapter "Establishing the correction coefficient of the cutting torque".

Practically, after centering the axes of the torque module and the cutting tool, a test item is fixed in the tool holder in which an internal thread is machined in which a screw is inserted. Using this screw, the known torques will be applied, adjusted on the torque screwdriver, and the values of the forces at the end of the arm of the torque module will be recorded.

Based on the data recorded by dynamometer A, the correction coefficient of the cutting torque will be determined.

At each mounting of the measuring system on a machine tool it is necessary to go through phase 1 “Aligning the equipment with the machine tool spindle” and phase 2 “Equipment calibration” in order to ensure the measurement accuracy and obtain correct data.

6.1.3 Phase 3. Carrying out the Actual Experiment

Fix the studied cutting tool in the drilling machine spindle, with the specific tool holder devices;

Adjust the drilling machine feed travel limiter switch to protect the measuring device from possible accidental processing;

Fix the test item made from the studied material in the test item fixture device;

Adjust the spindle speed and the feed;

Set the ”sampling time” on the dynamometers;

Start the data acquisitions for the dynamometers;

Start the drilling machine and with the mechanical feed and the spindle speed already adjusted, process a hole. Extract the cutting tool from the hole and stop the drilling machine;

Stop the data acquisition of the dynamometers;

Open an Excel file and every time the data obtained from each dynamometer is exported on the first ”sheet”, resulting in two ”sheets” with data referring to feed force and force component of the cutting torque. Save the file.

The experiment was repeated 3 more times to complete the holes in the test specimen.

6.1.4 Phase 4. Data Processing

The Excel file with the experimental data is opened and the cutting torque is calculated with the following data: the measured force, the arm of the torque module and the correction coefficient (paragraphs 5.6, 5.7).

In Figure 12 present the graph of the variation of the feed force and the cutting torque obtained experimentally.

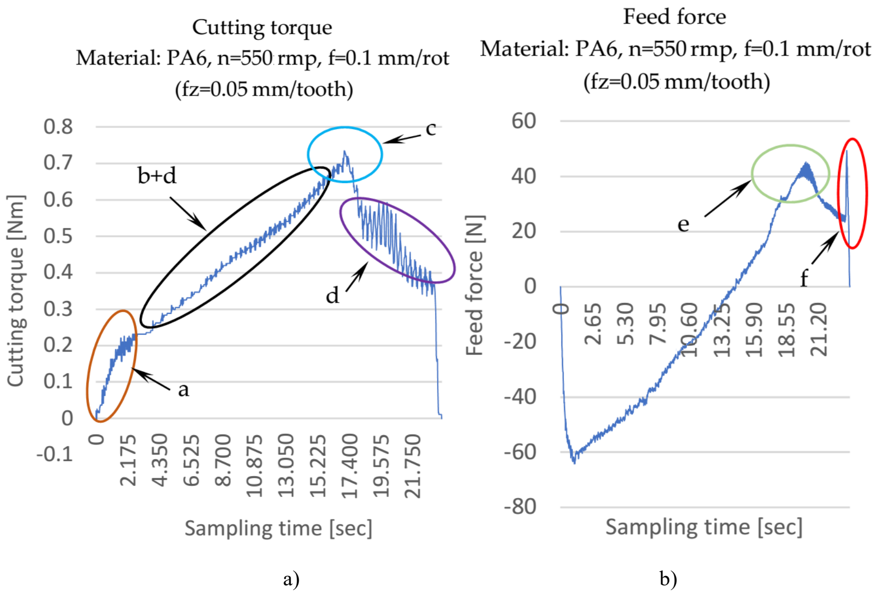

Figure 12

Variation of the feed force and the cutting torque: (a) cutting torque; (b) feed force

To highlight the repeatability of the measurements in Figure 13 present in the same graph the cutting torques for the 4 holes processed in the test specimen.

According to the research topic, processing and interpreting the data will continue.

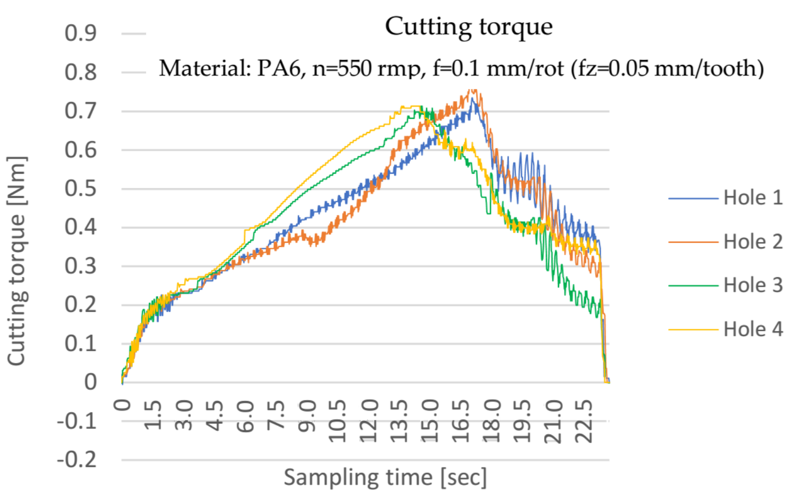

Figure 13

Repeatability of the measurements

6.1.5 Phase 5. Result Analysis

The graph in (Figure 12a) shows the evolution of the force component of the cutting torque from the beginning of the bore processing to the withdrawal of the drill from the hole.

The graph in (Figure 12b) shows the evolution of the feed force from the beginning of the bore processing to the withdrawal of the drill from the hole.

On the mentioned graphs (Figure 12) different areas can be identified:

a) the entry area of the point of the twist drill in the material;

b) continuous cutting area;

c) the drill exit area from the material;

d) the friction area between the drill and the wall of the processed hole. After the drill exits on the opposite side of the test item, both the feed force and the cutting torque do not decrease to zero (0) because the material tightens on the drill.

e) on the diagram of the feed force one can observe its evolution in time. Due to the helical blade, the material tends to climb along the tool like a nut. The fixing force of the test item fixture device is required so that the test item is not removed from the device.

f) the exit moment of the drill from the bore using the fast feed can be seen on the OX axis of time on the graph. There is an increase in the negative feed force due to the tendency to lift the semi-finished product from the device.

7 Analysis of the Measuring Method and System from an Economic Perspective

In this research an affordable system with which to perform exploratory tests and allow the development of research in the field of hole processing was designed and developed.

A comparative cost analysis is presented below.

The costs on the market of a ”turnkey” equipment amount to the values of 55000-65000 euros.

I value the conceived, designed and executed device to 3820 euros.

- Purchase of supplies (two dynamometers, an axial bearing, a radial bearing and assembly components) in the amount of 820 euro

- Self-managed activities valued at 3000 euro
- These activities can be split into design activities (10 days x 8 hours x 20 euro/hour = 1600 euro)
- Processing by cutting and mounting (50 hours x 25 eur/hour = 1250 euro)
- Other linked activities.

Therefore, the carried out device is 1/80 if it is related to the actual expenses from the value of an equipment on the market (Or 1/17 from the value of a piece of equipment from the market if it is related to the total expenses with the manufacturing of the device.)

A comparison of advantages and disadvantages is presented in Table 4.

Table 4

Advantages versus disadvantages of the measuring system

DEVICE		COMMERCIAL EQUIPMENT	
Low costs	+	-	High costs
Big size	-	+	Low size
Poor measuring range	-	+	High measuring range
High measuring accuracy	+	-	Low measuring accuracy
Usable only for hole processing (drill, tap, reamer, etc.)	-	+	Can also be used for milling processing
Each dynamometer has separate software and the purchased data must be merged into an Excel file.	-	+	Purchased data automatically ends up in a single file.
The cutting torque results from the multiplication of the force with the arm of the force	-	+	The cutting torque results directly.
Simple control and calibration.	+	-	Hard control and calibration.

Conclusions

Based on the information presented in this paper, the following conclusions can be highlighted:

- A method and a system have been developed for measuring the cutting torque and the feed force through which cutting experiments can be performed at a “cost efficient” level;
- A usable system has been developed to study the phenomena that occur during the processing of holes, threads and data acquisition for further analysis;
- The system can be used for drilling, tapping and reaming processes;
- The presented system and method can reduce the research costs in the field of drilling, tapping and reaming;

- It can be used routinely in the teaching process;
- The system, through its construction, increases the measurement accuracy of the incorporated equipment;
- The system allows the extension of research for several fields.

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