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A TOOL FOR BALL BURNISHING WITH ABILITY FOR WIRE AND WIRELESS MONITORING OF THE DEFORMING FORCE VALUES

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Abstract: *The present paper describes the construction and operational parameters of a specialized tool for ball burnishing that has capabilities for measuring and wirelessly transmitting the current deforming force magnitude during the burnishing operation. It can be used both for burnishing and for formation various patterns of regular reliefs on rotational surfaces using different types of lathe machines and CNC turning centers. The main construction elements and the principle of adjustment and operation of the tool are explained, along with the electronic components used for measuring and transmitting the deforming force values to the external client devices. The main advantages and constraints of the tool and opportunities for its future development and improvement are discussed at the end of the paper.*
Key words: *ball burnishing; regular reliefs; load cell; Wi-Fi; Artificial Intelligence of Things; Industry 4.0*

1. INTRODUCTION

There is more and more evidence recently for attempts the traditional machining processes be adapted to the contemporary requirements of the industry. Many research nowadays taking into account the principles laid down in the concept of Industry 4.0 to collect data from the processes, and their subsequent processing in order to extract useful information about the conditions under which it is carried out. Of particular interest are applications that can provide information on process parameters in real time. For example, Dobrota et al. have proposed an intelligent cutting tool [1], designed to control the vibrations of the tool tip in order to achieve better roughness of the processed surfaces. Tseng et al. reported creation of a smart tool holder, intended to measure the cutting force of turning tools in the finishing turning [2]. An indirect tool wear monitoring system with online measured cutting force and cutting temperature is proposed in [3]. A comprehensive review of the measurements approaches of the operational parameters and for tool condition monitoring of milling operations is given in [4], including force measurements, vibration measurements, acoustic emission sensors, current and power sensors, image and thermal sensors, etc. There are examples for measuring basic regime parameters not only for cutting operations, but also for grinding [5,6], ball burnishing [7,8], and for other manufacturing processes.

As can be seen from them, the measurements of the processes parameters are conducted, mainly using sensors connected to the measurement devices by wires. Sometimes this could be a suitable solution, when the work zone of the machine tool is open and there are no obstacles for the cables to pass through. However, the work zone of the contemporary machine tools usually is fully isolated from the ambient space using suitable enclosure, due to the occurrence of risks to the life and health of workers in the vicinity, environmental pollution, noise, etc. Moreover, their CNC devices are designed to prevent the processing cycle to start if the enclosure is not fully closed. These precaution measures however, make it difficult (and sometimes even impossible) data cables to be passed from the sensors outside of the working area of the machine, or require their extension to bypass the enclosure. This often lead to increase the possibility of inducing noise in transmitted signals, and higher risk for damages of the signal wires due to the machine tools actuators movements during the cycle execution. That is why, recently, special interest has been paid to devices, which can process and wirelessly transmit the measured data from the sensors to the external (i.e. located outside the work area) information-processing devices.

Research in the Internet shows that there are some commercial solutions, such as [9,10] for sensors data acquisition devices and wireless transmitting the measurements to the data processing system. The price of such measuring devices however, in most cases is too high for their wide use in the production processes for many manufacturing companies.

At the same time, IoT (Internet-Of-Things) devices are gaining more and more popularity nowadays. Based on wireless communication (both with each other and with remote resources via the Internet), they allows the collecting, processing and transmitting information from various sensors embedded in houses, offices, household and office appliances, vehicles, etc., which we use daily. Open-source electronics platforms, based on easy-to-use hardware and software, gives opportunities many people from whole over the world to get involved into development of many new IoT applications. This determines the rapid development and spread of these technologies on one hand, as well as the improvement and significant cheapening of the hardware (i.e. microcontroller units and sensors) used for their implementation. As example, some microcontroller devices and development boards of manufacturers such as Arduino, Expressif, STMicroelectronics, PlatformIO Labs, etc. can be indicated, which are focused on developing cutting-edge Wi-Fi-and-Bluetooth, low-power and low-cost, AIoT (Artificial Intelligence of Things) solutions.

Therefore, there is an interest in applying such of technologies, in order to avoid the above-described disadvantages of wiring the sensors in some machines with an isolated working area, on a reasonable cost.

The main objective of the present work is to create a tool for ball burnishing of rotary parts, which is intended to work with CNC turning centers, and which is able to send wirelessly data of the instantaneous values of the deforming force, to monitoring the burnishing operation.

2. TOOL'S DESCRIPTION

2.1 Main requirements of the ball-burnishing tool

In order to determine the main characteristics of the tool, initially it is necessary to define the scope of its application. The main goals that need to be achieved by using the tool can be defined as:

- Formation of regular reliefs of all five types [11,12] by ball burnishing operation onto external rotary surfaces, using various CNC turning centers;
- Possibility of processing parts made of different materials that have different physical and mechanical characteristics;
- Ability to measure the deforming force simultaneously, during the ball burnishing operation, and ability for both wires and wireless transmission of the measured data to the external acquisition and data processing devices.

Based on these requirements, the first important characteristic of the tool is the maximal deforming force, which it must provide. The deforming force depends on the maximal contact stresses in the surface layer of the processed material, in order to produce plastic deformation and this way to form so called "regular reliefs" [11]. The contact stresses depends also on the diameter of the deforming ball tool (which is used in this type of ball burnishing process) and on hardness of burnished surface. Because the contact between the spherical ball tool and cylindrical surface is none Hertzian, for the approximate calculations the Brinell hardness test formula is employed:

$$HBN = \frac{F}{\pi \cdot D \cdot \left(D - \sqrt{D^2 - d^2}\right)} \qquad (1)$$

where HBN, kgf – is the Brinell hardness number of the material; F, kg – is the pressing force; D, mm – is the diameter of the hard ball, and d, mm – is the diameter of the imprint of the hard ball in the material surface.

Because for the most used in practice materials the HBN is known from the carried out test in the manufacturer, or can be measured easily, formula (1) could be expressed as follow:

$$F = \pi \cdot D \cdot HBN \cdot \left(D - \sqrt{D^2 - d^2}\right) \qquad (2)$$

It can be seen from (2) that the two others components are the ball diameter and the imprint diameter. According to the abovementioned requirements, the tool must work with different CNC turning centers, even with those, who have comparatively small working area. Therefore, the overall dimensions of the tool also should be kept as small as possible. Hard balls from rolling bearings with small diameters could be suitable in this case. On the other hand, the imprint diameter affect the plastically deformed trace widths, which determine the size of the obtained patterns of the regular reliefs. Taking into account the HB values of the most commonly used materials (HBN ≤ 500), setting the maximum diameter D of the deforming element to be no greater than 8 mm, and for the diameter of the imprint d up to 0.55 mm in the formula (2), for the deforming force F ≈ 120 kg (or F = 1.18 kN) is obtained. Therefore, the tool should be dimensioned to reach such a maximum value of the deforming force.

2.2 Description of the ball-burnishing tool construction

The ball-burnishing tools construction is shown on the figure 1. The most important parts from it are the compressive spring, which provides the deforming force and the load cell transducer, which measure it. Based on calculated maximum deforming force value, a compressive spring (Henlllich, CZ, model 80/1/1) was chosen as elastic element for the burnishing tool (see pos. 10 in the Fig. 1). This spring is made of ∅5 mm wire from C-class spring steel 1.1200 (EN 10270-1). It has minimal dimensions: length L= 41 mm, outer diameter Do=30 mm, and can provide maximum deforming force of 1267 N.

A SIKA, DE, type FCM load cell is used as force transducer (see pos. 12). It allows measuring loads up to 5 kN and also has minimal dimensions: outer diameter ∅35 mm, and length of 15 mm.

The rest of the tool parts are designed in accordance with the dimensions of the aforementioned two basic elements, and are based on the experience, described in [13]. The front end of the deforming tool (see pos. 14, 15 and 16) is designed to be able to work with three changeable diameters of the spherical deforming elements, respectively D = 4, 6 and 8 mm. The front bushing (pos. 17) provides a minimum radial clearance within 0.02 mm, which is important condition for the precise formation of regular reliefs when the deforming tool perform reciprocating motion, relatively to the longitudinal axis of the rotary workpiece. The spring compression adjustment, and therefore the magnitude of the deforming force F, sets by the standardized screw M14 (see pos. 2), which is placed in the rear side of the tool's housing. When it is screwed in, its face moves the sleeve (see pos. 9) axially forward, causing the spring to compress. Conversely, when the screw is unscrewed it causes the spring to relax. The front nut (pos. 18) is screwed to the front end of the housing (pos. 1), thus balancing the deforming

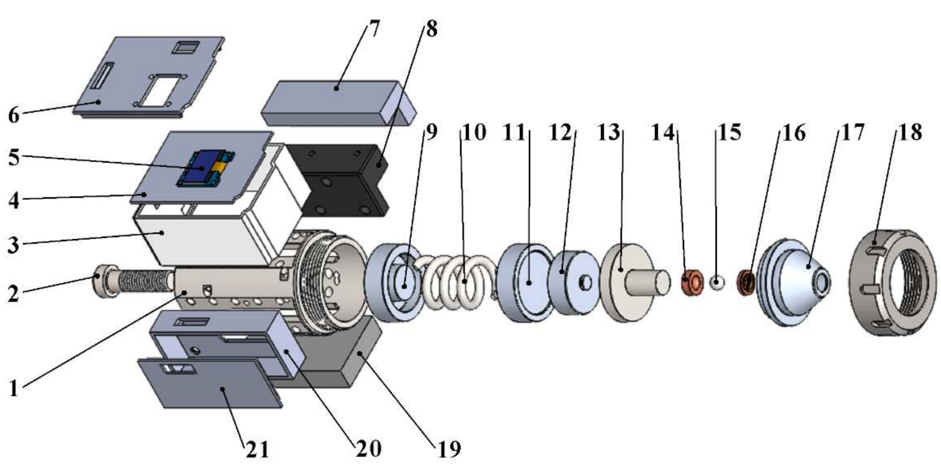

Fig. 1. Exploded view of the ball-burnishing tool assembly and its components.

a) b)

Fig. 2. Setup of the ball-burnishing tool in the CNC lathe turret: a) general view; b) closer view.

force and prevents its self-disassembly, when the ball is not in contact with the burnished surface.

The ball-burnishing tool sets up in the CNC machine's turret by using the L-shaped plate (see pos. 8). The clamping cross-section of the plate has basic dimensions 16×16 mm, but two more additional plates (see pos. 7) allows to obtain 20×20 or 25×25 mm cross-sections accordingly. In this way, the tool can be used with different types and size of tooling respectively. Therefore, the first of the main requirements is satisfied. The assembled ball-burnishing tool, mounted in the turret of the CNC lathe machine type ST201 is shown in the figure 2 a, b.

2.3. Description of the hardware used

In accordance to the third main requirement, an MCU device is used (see Fig. 3), which allows measuring the deforming force during the burnishing operation execution.

An ESP8266-12 (Espressif) system-on-chip (SoC) device was employed that integrates an enhanced version of Tensilica's L106 Diamond series 32-bit processor and on-chip SRAM [14]. This MCU supports Wi-Fi protocols 802.11 b/g/n (2.4 GHz), up to 72.2 Mbps for wireless data transfer, and serial peripheral interface (SPI) for communication with small external electronic devices. Its operating voltage is between 2.5 and 3.3V and average operating current is 80 mA (when it is in active mode), which makes it suitable to use with autonomous power supply. In the current application, the ESP8266-12 is integrated in the Arduino Uno footprint developing board, called WeMos-D1R2, because it has RS-232 serial micro-USB port for connection to the computer. This allows

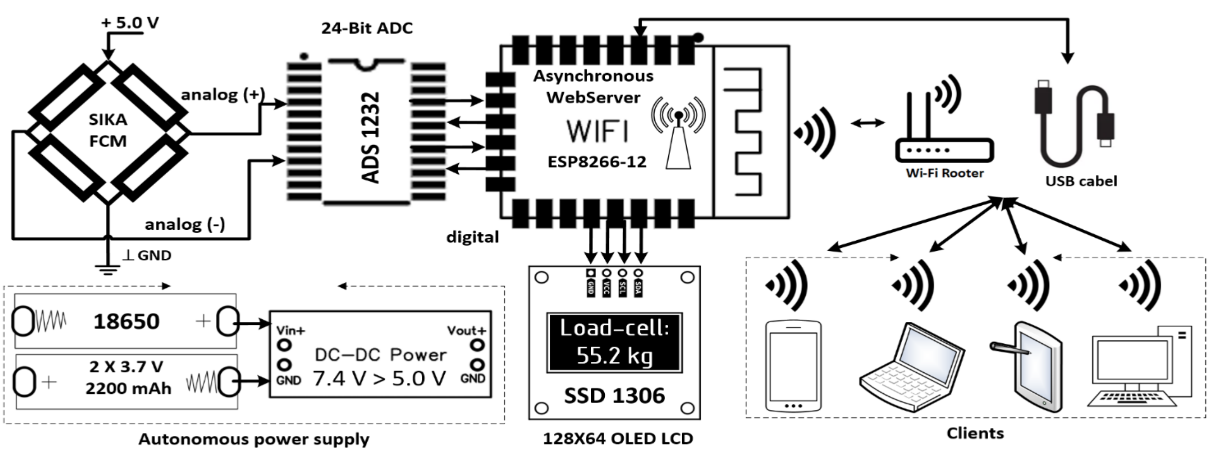

Fig. 3. Diagram of the tool's measurement system for deforming force monitoring.

using Arduino IDE platform for easily programming the ESP8266-12, calibration the load cell and wire mode of deforming force monitoring.

The analog signals, generated from the load cell FCM, firstly converts into digital, by using 24-Bit delta-sigma analogous-to-digital-converter (ADC), model ADS1232 (Texas Instruments, US) [15], and then fed to the ESP8266-12's SPI-inputs (see Fig. 3). ADS1232 ADC is designed especially for bridge sensor applications. The low-noise programmable gain amplifier has a selectable gain of 1, 2, 64, or 128, supporting a full-scale differential input of ±2.5 V, ±1.25 V, ±39 mV, or ±19.5 mV. The delta-sigma ADC provides a maximum of 23.5-bits effective resolution, and supports two data rates: 10 SPS (samples per second) and 80 SPS. Operational modes of ADS1232 can be set by using suitable combinations of low or high levels to the corresponding pins, which can be controlled programmatically by ESP8266-12.

An OLED LC display, type SSD 1306, is also connected to the controller ESP8266-12. It is mounted on the cover cap of the housing in which the electronics part is installed (see pos. 3-6 from Fig. 1). Its purpose is to display some valuable data at power-up, such as the name of the SSD network and the IP address of the server, where the deforming force can be monitored, as well as the value of the current calibration constant. After this initial data, the display shows the current value of the deforming force until the device is switch off. This makes it easier for the operator to set the desired value of the deforming force, before starting the ball-burnishing operation. In addition, this indication can also be used for (indicative only) control of the deviations from roundness and/or cylindricity of the workpiece, if this is relevant.

The hardware set has autonomous power supply (see Fig. 3, and pos. 19 from Fig. 1), which consist of two Li - Ion 3.7 V rechargeable batteries (type 18650) connected in series, and a LM2596 DC-DC converter to reduce the voltage from 7.4 to 5.0 V. The duration of continuous operation of the device depends on the capacity of the batteries used. For example, if batteries have 2200 mAh capacity the continuous operation duration of the described set is about 14 hours, until next recharging.

Since the presented tool is also intended to perform experimental studies of the ball burnishing process, the 80 SPS sampling rate may not be sufficient in certain cases. That is why it is possible the sensor to be connected directly (but through a cable) to an external ADC that can provide the needed for the experimental research sample rate. The connectors located in the left-side box (see pos. 20 and 21 in the Fig. 1) can be used for that purpose.

To monitor the deforming force wirelessly, in addition, a Wi-Fi router is required to connect the asynchronous server installed in the ESP8266-12 with the client devices (see Fig. 3). Any Wi-Fi router that supports the protocols 802.11 b/g/n (2.4 GHz) and with sufficiently cover range can be used for this purpose. The ESP8266-12 also has a built in EEPROM memory with size of 4kB where certain data can be stored. For instance, this could be Wi-Fi passwords, the determined calibration constant, etc. that should remain memorized if controller is restarted or switched-off from power supply. In this way, there is no need calibration or authentication to the Wi-Fi network to be done every time when it start-up.

2.4 Description of the software used

The ESP8266-12 is programmed using Arduino IDE via RS-232 USB between computer and the WeMos-D1R2 board. The ESPAsyncWebServer library [16] is employed to build an asynchronous web server (AWS) (see Fig. 4. a), which has several advantages, as follows:

- It able to handle more than one connection at the same time. This means that more than one client can be connected and receive data for deforming force at the same time;
- The server immediately is ready to handle other connections, while the current response is sending in the background;
- It offers simple template processing engine to handle HTML, Java, etc.

The last option allows the client devices to use their web browsers for access the webserver and launch a suitable HTML template to have monitoring and record the deforming force magnitude values. The template has also ability for graphical representation of the deforming force values, by using the open-source

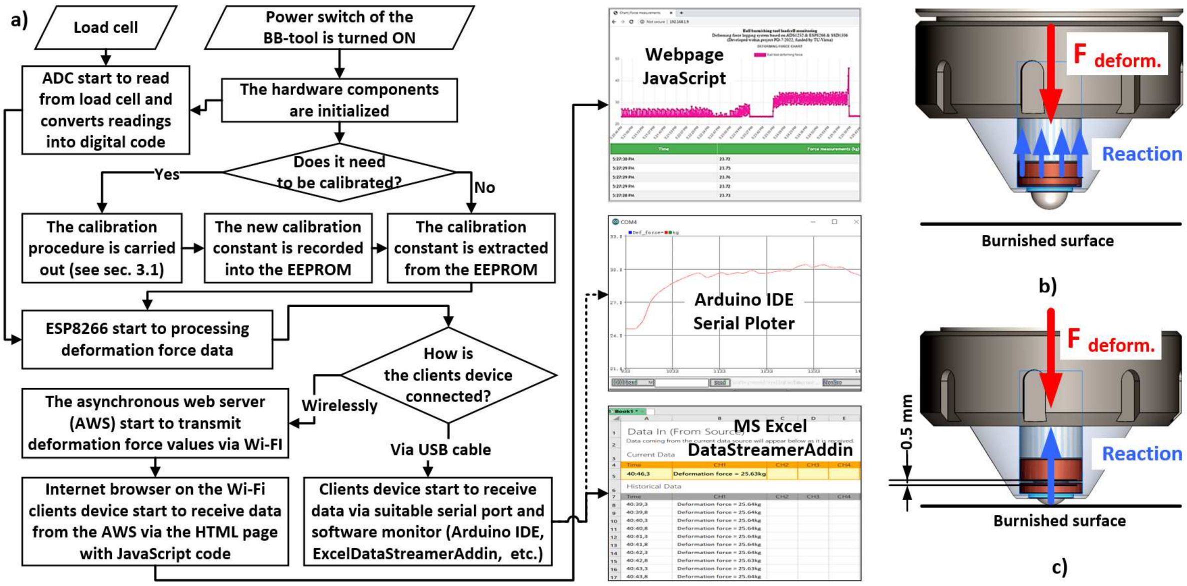

Fig. 4. a) An algorithmic diagram, which describes the measurements system's operation principle; Diagrams of the deforming force balancing when the ball: b) is not in contact, and c) is in contact with the burnished surface.

JavaScript library "Chart.js". Another possible way to monitor the deforming force is to use wired connection via USB cable between WeMos-D1R2 and the client device, employing any suitable serial port reading software application, as it is shown in the Fig. 4. a.

3. SETTING UP AND ADJUSTING THE BALL BURNISHING TOOL FOR WORK

3.1 Calibration procedure

Before to start using the tool, it must be calibrated in order to adjust the readings of the deforming force. For that purpose, a procedure has been created, which is executed when a certain key letter (for example "r") is sent via the Serial monitor of the Arduino IDE to the ESP8266-12 controller (see Fig. 4. a). After that, the tool is loaded with a known load (i.e. weight etalon) and its value is input via Serial monitor to the controller. Than the calibration constant (CC) is determined automatically, using the equation:

$$CC = \frac{EW}{(RV - TR)} \qquad (3)$$

where: EW is the etalon weight of the load applied, RV is the current read value from the ADC, and TR is the tare value that balances the resistors bridge in the load cell.

Calculated in this way value for CC is memorized in the EEPROM of the ESP8266-12. The next time when the tool is (re)started, the CC value is read from EEPROM and use in the deforming force calculations (see Fig. 4. a). The calibration procedure should be carried out periodically, especially after long periods when the tool has not been in use.

3.2 A peculiarity when setting the deforming force

When the burnishing tool is not in contact with the burnished surface, the face of the plunger is in contact with the face of the sleeve (see Fig. 4. b). In this way, the spring load is balanced when tool is idle (during its positioning or prepositioning), and the ball is free of load. When the tool starts to processing the burnished surface, the ball needs to be sunk about 0.5 mm inward direction (Fig. 4. b, c). In this way, the face of the plunger stops to contact with the sleeve and the spring load begin to apply onto the ball and burnished surface respectively. When the deforming element is moved inward however, an additional compression of the spring will occur, which will slightly increase the overall magnitude of the deforming force. Therefore, when the ball-burnishing tool is adjusted for work, this additional spring compression must be taken into account.

When adjusting the deforming force, the machine operator can be guided by the readings, which are visualized on the tool's OLED display (see pos. 5 from Fig. 1).

4. CONCLUSION

According to the main goal defined, a specialized tool for ball burnishing operation of rotary parts was designed and manufactured. The main requirements to the tool were satisfied accordingly. It has the minimalistic dimensions but is able to provide enough deforming force to ball burnishing the different types of materials (with Hardness Brinell up to 500). It can works with different types of lathe machines and CNC turning centers, even with those, who have small size of the working space. The presented tool has abilities to measure simultaneously and transmit the measured data for the deforming force, both by wire (in case of more precise measurements) and wirelessly. The wireless mode uses standardized Wi-Fi protocols and devices, and it can be applied for remote monitoring of the ball burnishing operation, from several different clients at the same time. The tests conducted with the tool shows that asynchronous server used can support up-to five clients on a distance 15 m from the Wi-Fi router. The software resources and tools used to program the asynchronous server are easy-to-use and open source.

The main constructive and operational characteristics of the ball-burnishing tool can be summarized as follow:

- Overall dimensions (max): length 150 mm, width: 100 mm, height: 105 mm;
- Dimensions of the clamping plate: 16×16 mm (20×20 and 25×25 mm also are possible using additional plates);
- Deforming force magnitude: up-to 1180 N (≈120 kg);
- Spherical deforming elements diameter: 4, 6 or 8 mm;
- Load cell: Sika, FCM, allows maximum measured load up-to 5 kN, and rated characteristic value 2 mV/V;
- ADC, ADS1232 (Texas Instr.) with 23.5-bits effective resolution, and sample rate 80 SPS;
- Wi-Fi device: ESP8266-12 (Espressif), 802.11 b/g/n (2.4 GHz), up to 72.2 Mbps;
- Power supply: 2×18650, Li-Ion batteries, 3.7 V, 2200 mAh.

The described above ball-burnishing tool should not be perceived as a fully completed commercial development. At this stage, it is just an experimental model that makes it possible to carry out further research on the ball burnishing process on rotary surfaces, in order to create regular reliefs on them, using CNC turning centers.

The team's future work will be focused on following directions": to achieve smaller sizes of the tool's electronic components, higher sampling rates of the deforming force, and to improve the client-server exchange information scheme, by creating an opportunity for remote control the controller ESP8266-12 and the ADC device through relevant commands submitted by the clients.

The demonstrated scheme can also be implemented for other machining tools used in machine-building production in the future.

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ECHIPAMENT PENTRU NETEZIREA PRIN RULARE CU BILE ȘI MONITORIZAREA WIRELESS A VALORILOR FORȚEI DE DEFORMARE

Lucrarea de față descrie parametrii constructivi și de funcționare ai unui echipament pentru netezirea prin rulare cu element deformator sferic, capabil să măsoare și să transmită wireless informații privind mărimea forței de deformare în timp real. Echipamentul poate fi folosit atât pentru netezirea suprafețelor, cât și pentru obținerea unor texturi cu reliefuri regulate pe suprafețele de revoluție, utilizând strunguri și centre CNC de prelucrare prin strunjire. Sunt prezentate elementele constructive, modul de funcționare și de reglare a echipamentului, împreună cu subsistemul electronic utilizat pentru măsurarea și transmiterea valorii forței de deformare către dispozitive externe. În partea finală a lucrării, sunt menționate principalele avantaje și constrângeri ale echipamentului, precum și posibilitățile de dezvoltare și îmbunătățire a echipamentului în viitor.

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