DEVELOPMENT OF A CLOSED-LOOP CONTROLLER FOR FILE TEETH MANUFACTURE USING AN INDUSTRIAL MACHINE

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Abstract. *In this paper the mechatronics system, as well as the results of the close-loop control of the chisel penetration depth implemented in an industrial file machine will be presented and discussed. The generating of the file cutting edges is made by penetration, due to impact of a cutting tool, which creates a plastic deformation on the file body. The chisel penetration depth is surely the most important factor of the final quality of a file. The main constraints of the existing machines are the adjustments which are carried out by the operator, relying on his experience, using the blowing noise and the visual analysis of the produced files, as control parameters. This means that the files are manufactured on an empirical basis relying on subjective factors, which does not permit a constant quality of the whole production.*

Keywords: *Mechatronics, Instrumentation, Kinematics and Dynamics, Mechanical Design*

1. Introduction

The mechanical filing operation is made using tools (files) with multiple cutting edges in one plane or curved surface, acting as cutting elements to remove, by plucking out, material from the work piece. These cutting edges are the most important parameter on the performance of that mechanical operation.

The experience shows that the most efficient way of generating these cutting edges is by penetration, by impact, with a rate that easily achieves 200 Hz, of a cutting tool, which creates a plastic deformation on the file body, with the shape of sharp edges, which work as cutting edges. Figure 1 shows a sequence of pictures that illustrate the way of generation of file teeth.

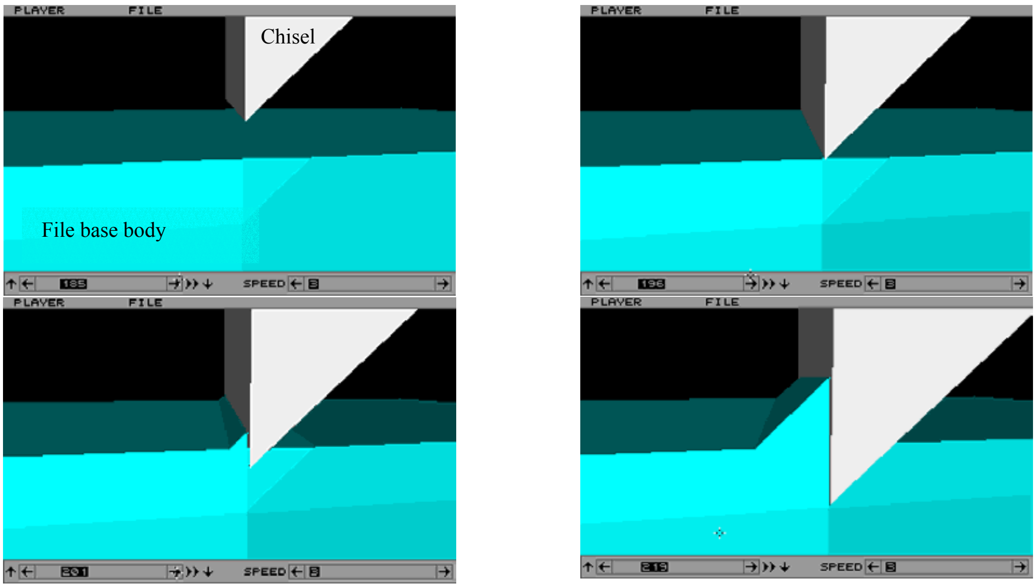

Figure 1. Simulation of the mechanical operation involved in the creation of file teeth.

The present research work has been developed with the cutting file machine OBJECKT-77563, which is shown in Fig. 2. In Fig. 3 is represented the mechanical system relating to the file teeth production, usually named as *cutting bench*.

As it was shown by (Seabra and Silva, 2000), the file teeth are produced by impact of the cutting beater (system composed by pin, cylinder and chisel), with a reciprocate movement. To generate this movement, the cutting bench has a “wheel-with-rebounds” (cam) that allows the pin (follower) moving up when rotating. This will lift up the cylinder, to which the chisel is attached, which immediately falls down, when reaching the up dead point, impelled by both, the spring and its own kinetic energy. The impact energy of the chisel depends on the relationship of the regulations of the spring force and the maximum distance between the chisel and the file (adjusted by the presser foot).

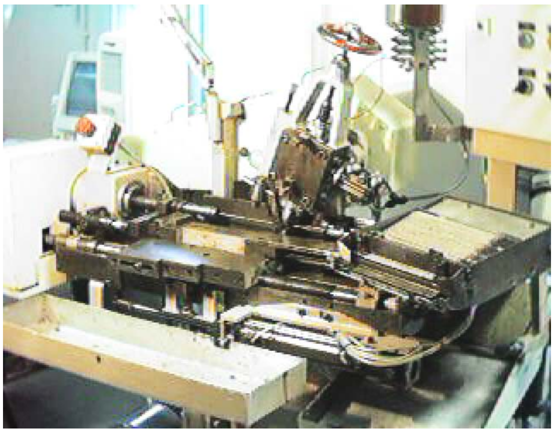

Figure 2. General view of the cutting round file machine.

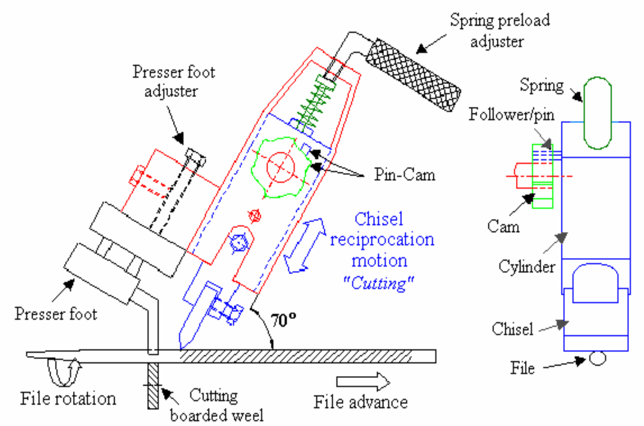

Figure 3. Schematic representation of the cutting bench.

The depth of the penetration is probably the most important factor of the final quality of a file. The main constrain of these machines are the adjustments carried out by the operator, relying on his experience, using the blowing noise and the visual analysis of the produced files, as control parameters. This means that the files are manufactured on an empirical basis relying on subjective factors, which does not permit a constant quality of the whole production (Seabra and Silva, 2000).

The main purpose of this research work, being developed at the University of Minho in a partnership with the *Bahco Oberg* Company, which belongs to the USA multinational group Snap-On, is to eliminate the described subjectivity factors by means of the evolution of the present all-mechanical system into a mechatronics one. This will allow the automatic control of the mentioned penetration depth, giving to the system the desired reliability and flexibility.

2. Development of the mechatronics system

2.1. Objectives and definition of the problem

The quality of the teeth is the main problem of the process of the file production. To ensure that a file achieves the desired quality level, the depth of penetration of the chisel (cutting operation), which defines the height of the teeth, shall be under a given tolerance related to a standard value (optimization of the file cut performance). Figure 4 shows typical examples of produced round files.

a) b) c)

Figure 4. a), b) Files without quality, respectively for diminutive and excessive height of the teeth, c) File with quality.

The verification process of the file quality is made by sampling. The quality tests consist on a visual inspection and an experimental test of file cut performance. Although it is recognized that this sampling process is the standard method of analysis in most of the production processes, the experience shows that in the case of the production of the teeth of the files it doesn't assure the constancy of maintenance of quality levels required for the process.

This is due to the fact that in the production of the file teeth many parameters are involved with the inherent difficulty to control and predict their evolution along the time. The most relevant are related with the cut performance of chisel, the temperature of operation of the machine, the force-deformation characteristic of the spring Belleville and the wear of mechanical components of the machine directly involved in the cutting operation (cam, pin, cylinder, etc). It is the operator of the machine that compensates the variation of these factors, through the tuning of main regulations (pre-tension of the spring and presser foot), using as control factors, the noise generated by the chisel cutting action and the visualization of the produced file teeth, trying with this keep correctly the depth of penetration of the chisel. This depth of penetration of the chisel is one of the main parameters which define the quality of a file. Being so this is an empiric process, that doesn't guarantee the maintenance of a pattern of quality.

On contrarily, the mechatronics system developed in this work performs the control of quality of each file, eliminating the inconveniences associated to the empiricism and subjectivity early referred. For each file, at least 500 samples of the depth of penetration of the chisel are acquired, which represents the analysis of about 500 teeth in a total of approximately 4000, going this way from a sampling of files to a sampling of teeth of each file. According with the quality of the teeth analyzed in each file, the system control give instructions that allow, by appropriate devices, the separation of the files produced with low quality.

Furthermore, with the developed mechatronics system it is possible to undertake preventive maintenance in order to reduce the mechanical problems associated to the machine components wear, which means an appreciable decrease of the costs associated to the maintenance and to the production stop times of the machine.

2.2. Description of the adopted mechatronics system

The concept of mechatronics design was considered appropriate to the present work with the objective of getting the automatic control of the main regulations of the machine in order to keep the depth of penetration of the chisel under values that guaranteed the production of the teeth in the quality limits.

This automatic control is carry out in two different stages:

- The first one refers to the initial regulation of the machine (setup), where the positioning of the pressure foot, as well as the pre-tension of the spring are automatically adjusted, in order to assure that the machine when the production starts, it will produce an adequately chisel penetration depth.

  To ensure the repeatability in the machine setup, it is always necessary to execute that initial regulation with the pin/follower positioned in a specific point of the cam. This is because an alteration of the follower's position changes the values of adjustment previously defined for the pressure foot (distance between chisel to the file), as well as for the spring pre-tension.

  The regulation is performed in one of the six points more eccentrics of the cam, which correspond to the top of one rebound. The reason of this choice was due to the fact of occurring in the tops of the rebounds a dwell of the pin/follower. This choice is reinforced due to the fact that the pre-tension value to adjust in the machine setup corresponds to a value of deformation spring smaller than the eccentricity of the cam.

  For the automatic positioning of the pin/follower on the point more eccentric of the cam a sensor of angular position (encoder) is used, as well as the main motor of the machine with an inverter to reduce the speed of the cam rotation. On that point, the pre-tension of the spring is regulated for a predefined force, read by a force transducer. Afterwards it is made the regulation of the pressure foot based in the use of an electrical signal of detection of the contact between the chisel and the file which will serve from reference to the distance to adjust between both.
- The second stage refers to the machine in production, when it is performed the close-loop control of the penetration depth. For that, it was firstly necessary to acquire, with a high rate, a signal of displacement of the chisel and an electrical signal of detection of the contact between the chisel and the file followed with a data analysis to compute the penetration depth. According to the obtained error, a correction output is produced to adjust the force of the spring, in order to keep the penetration depth correctly.

The design of this automatic control was decomposed in three design components, mechanical, electronics and computing, as it is shown in Fig. 5.

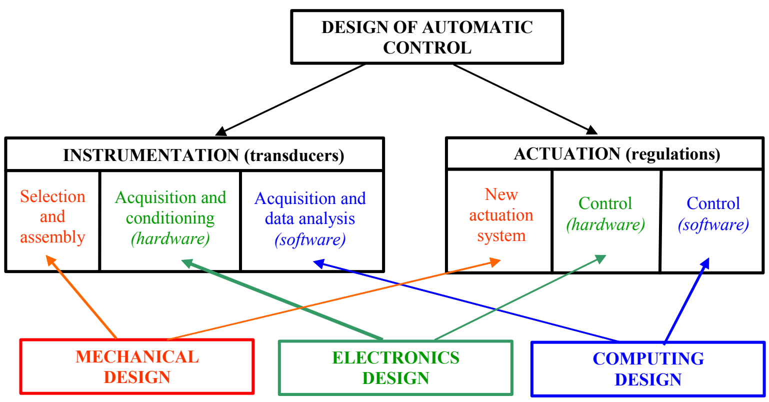

Figure 5. Scheme of the automatic control developed for the depth of penetration of the chisel.

2.3. Prototype of the mechatronics system

The experimental analysis was carried out in the machine-prototype constructed on basis of the mechatronics design, previously presented, that performed the control automatic of the main regulations of the machine.

In Fig. 6 and Fig. 7 they are presented, respectively, the configurations initial and final of the machine for which it can be identified the changes implemented in the cutting bench of the machine.

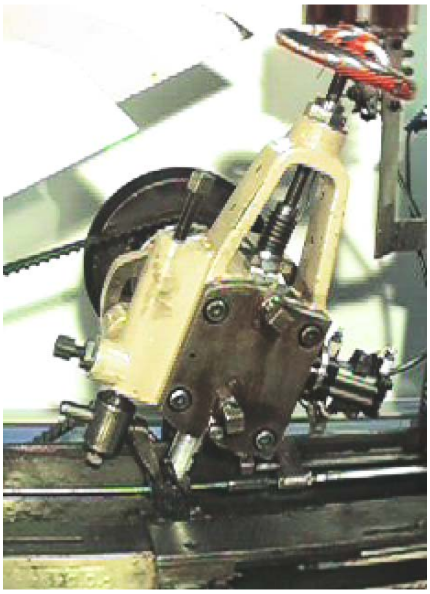

Figure 6. Machine - Initial.

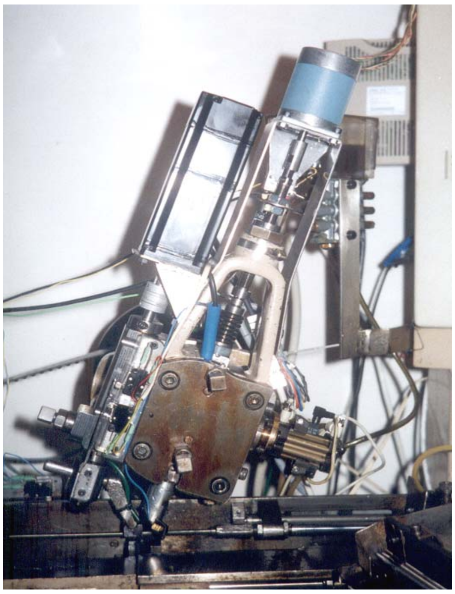

Figure 7. Machine - Prototype.

The experimental cutting tests were undertaken as following.

In a first stage the machine setup was performed allowing the automatic adjustment of the presser foot (distance chisel-file) and the spring pre-tension, in accordance with the open-loop control presented in the Fig. 8. An encoder was used for the automatic positioning of the pin into the more eccentrics point of the cam. It was attached to the cam rotation axis (Fig. 9) of the main motor of the machine with an inverter to reduce the speed of rotation of the cam. The output frequency value of the inverter, that determines the motor rotation speed, was defined by an analogue output of the acquisition board. In that position of the cam, the pre-tension of the spring was regulated by a step motor, until the setup force, gave by the piezoelectric force transducer, was achieved. The motor steps were obtained by an appropriate driver, which receives pulses from a digital output of the acquisition board. At the same point of the cam, the regulation of the presser foot was also carried out by the servo motor, based on the use of an electric signal contact chisel-file, which works as the reference distance for the setup distance.

The contact signal was obtained by an electrical contact, being the file connected to the ground polarity. That signal was acquired by an analogue channel of the PCI-1200 board. The loss of contact chisel-file corresponds to a signal of +5V and the contact to a signal of 0V.

The regulation of the distance chisel-file was carrying out by a servo motor using its driver (Fig. 9). The signal received by the motor driver was given by a digital output of the acquisition board through an electronic circuit interface specifically developed for the purposes.

To assure the automatic control of the penetration depth, it was necessary firstly to know exactly the values of the main parameters related with the file teeth production, as well as, the spring force and the displacement of the cutting beater to produce a quality file with a correct penetration depth. For that reason, a LVDT transducer (Linear Variable Differential Transformer) has been selected for measuring the displacement of the cutting beater, which has a good accuracy and, as the measurement is done with no contact (Bentley, 1997 and Schaevitz, 1999), works perfectly well under conditions of high vibrations/frequencies and accelerations. For the measurement of the spring force a piezoelectric force transducer was selected, due to the fact that this technology is the most appropriated to measure dynamic forces at high frequencies (Jacob, 1989 and Kistler, 1999). Figure 10 shows the transducers arrangements in the cutting bench of the industrial file machine.

The analysis of the experimental tests was made using the results obtained by the software developed in the editor LabVIEW. This software was developed based on the computing work, developed to achieve the automatic control of the machine, related to the acquisition and treatment of the transducers data, as well as, the control of the main regulations of the machine.

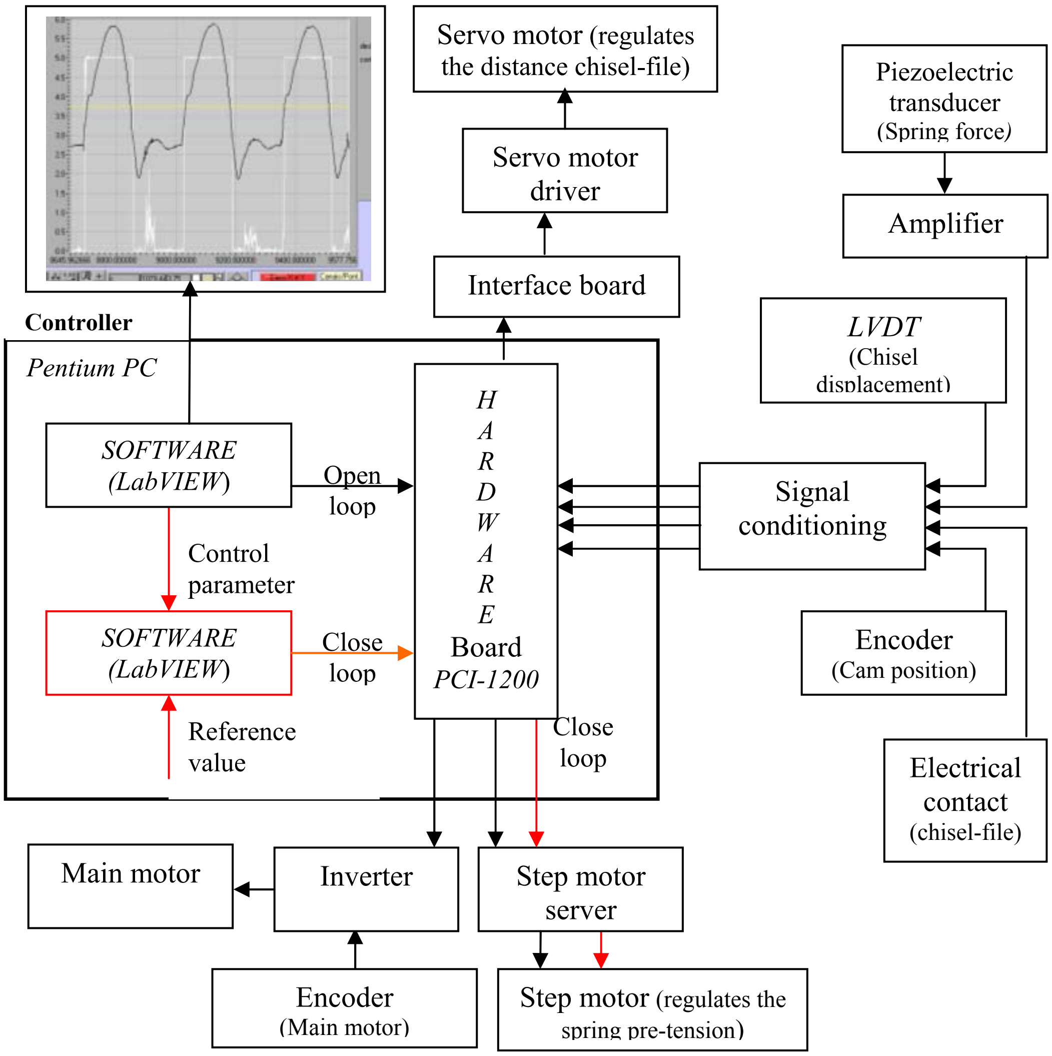

Figure 8. Detailed schematic representation of the implemented control of the file teeth production (the closed-loop control includes the draw in red).

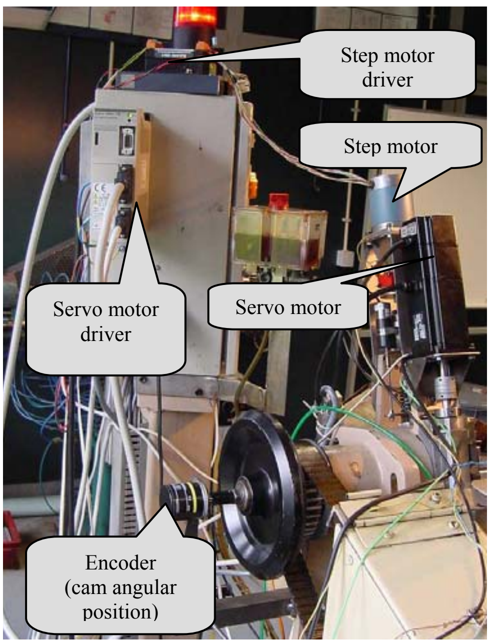

Figure 9. Servo and step motor drivers.

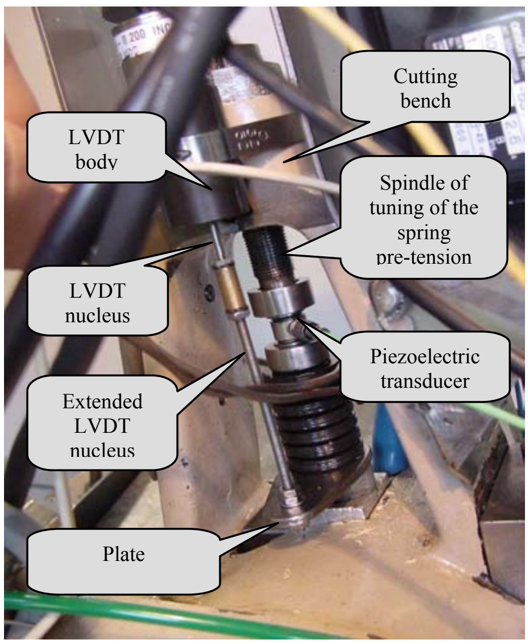

Figure 10. LVDT and piezoelectric transducers.

The data acquirement was obtained from the PCI-1200. It receives four analogue signals (LVDT, piezoelectric, electric contact and encoder), from a signal conditioning board specifically developed and built for the application, and sends them to the controller (PC + software LabVIEW) that does the data processing, calculating the value of the depth of penetration of the chisel.

Figure 11 shows the most significant points of the acquired signals of force, displacement and contact. These are obtained automatically by the software, using subroutines specifically developed for this work. The depth of penetration of the chisel, which is the control parameter, was obtained by the difference between the initial point of contact chisel-file (d cont.) and the minimum point (d min.) of the displacement signal.

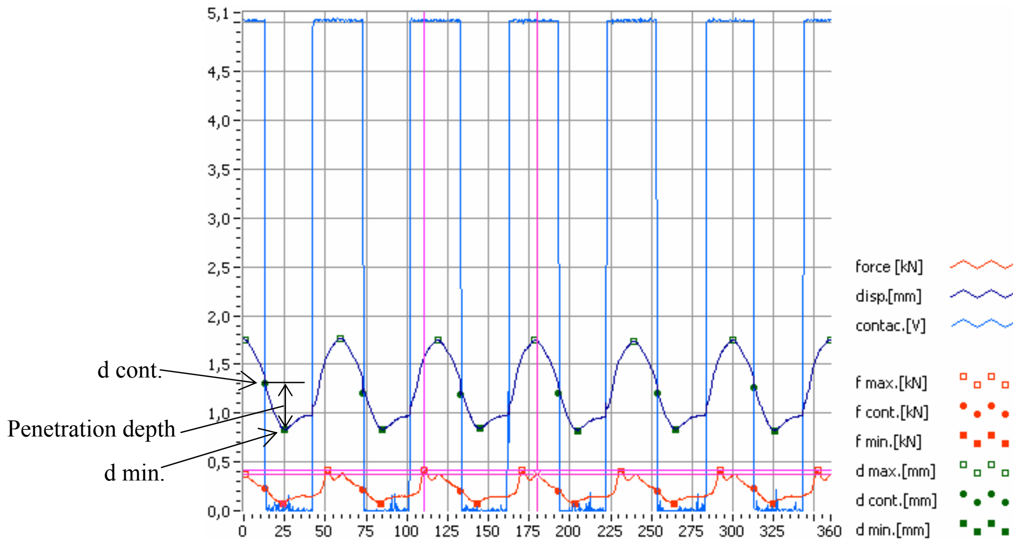

Figure 11. Waveforms of spring force, chisel displacement and contact chisel-file for a whole rotation of the cam (six rebounds) obtained in conditions of normal operation of the machine (xx axis - degrees).

To obtain the close-loop control of the penetration depth, two reference intervals are used. One, the larger, named as quality interval, corresponds to a chisel penetration between 0,35 and 0,55 mm. The other, more narrow, between these limits, named as control interval, was fixed between 0,43 and 0,47 mm When the value of statistical interval of the penetration depth (normal distribution for an interval of trust of 95%) goes out from the quality interval, the controller stops the files production. If the statistical interval is inside of the control interval, the controller keeps the value of the spring force (step motor stopped). If it is higher, or lower, it decreases or increases the spring force (step motor actuation), respectively, according with the penetration deviation (error), performing the control operation. Figure 12 shows the experimental data of cutting file tests used to obtain the close-loop control operation, given by the relation of number of motor steps versus penetration depth (control parameter).

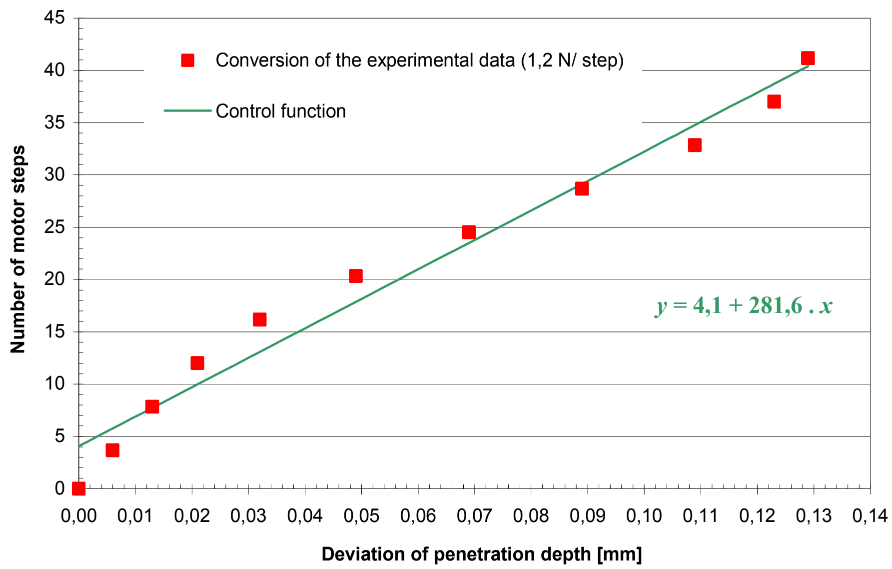

Figure 12. Close-loop control function.

3. Experimental results of close-loop control

The experimental tests have been performed with the following parameters of machine operation, regulated in the setup: cutting chisel frequency of 187 Hz, distance chisel-file of 0,6 mm and spring pre-tension of 315 N.

All the tests of file teeth production were made with a new chisel (maximum sharpness) in order to properly compare the results in terms of the chisel penetration depth, which, as early referred, was assumed as the control parameter.

Figure 13 shows the results of the close-loop test performed with the maximum number of adjustments per produced file (correction of the spring force) that was possible to carry out with the developed control system. This value is limited to the maximum of 5 adjustments, based on the comparison of the time of production of the file (22 seconds) and the totality required for acquisition, treatment and actuation.

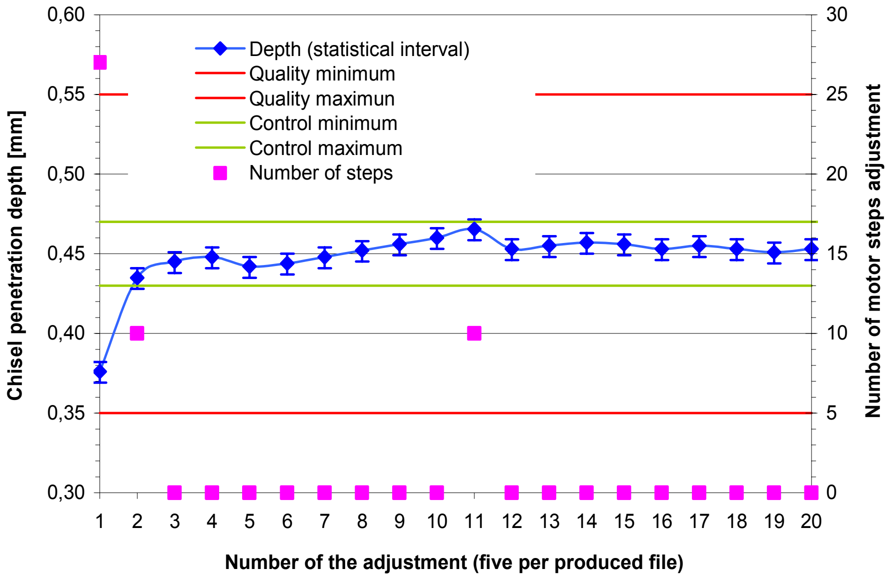

Figure 13. Close-loop control of chisel penetration depth with 5 adjustments per produced file.

By the analysis of the Fig. 13 it is verified that the control parameter of penetration depth converged quickly to the control interval, being necessary only two adjustments. It shall be noticed that in twenty possible adjustments (four produced file) only three were performed.

For the analysis of the influence of the adjustments frequency in the control parameter, two additional tests were made, on a close-loop basis. One, with one adjustment per produced file, and another, with one adjustment for each five produced files. Those results are shown, respectively, in Fig. 14 and Fig. 15.

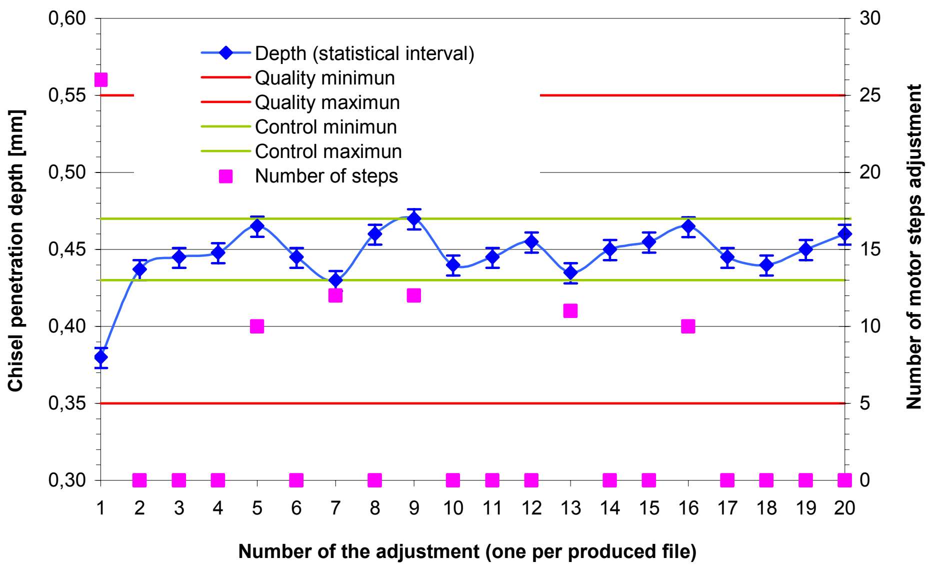

Figure 14. Close-loop control of chisel penetration depth with 1 adjustment per produced file.

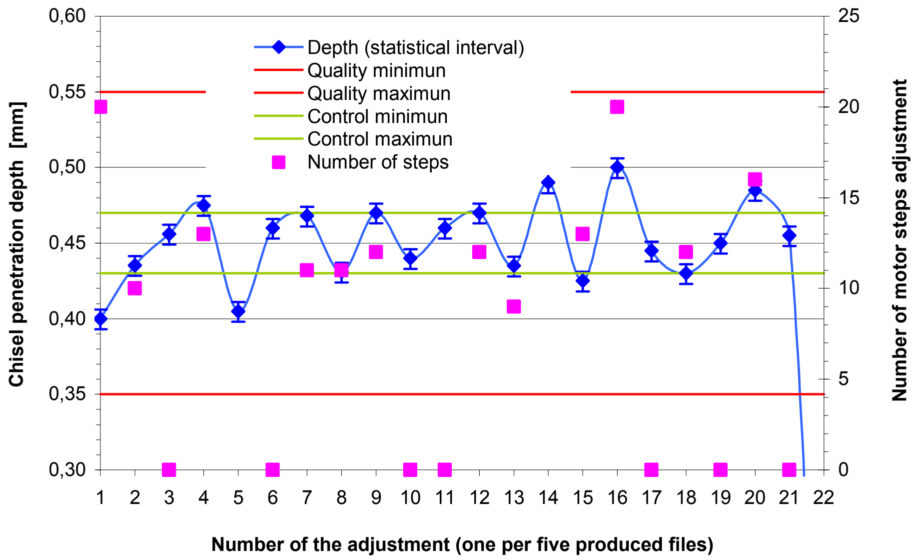

Figure 15. Close-loop control of chisel penetration depth with 1 adjustment per 5 produced files.

Figures 14 and 15 show a different evolution from the penetration depth in relation to the test carried out with a larger frequency of adjustments (Fig. 13). They present larger amplitude of values, specially the test performed with just one adjustment for each 5 produced files. It was concluded that it is preferable to use the regulation in close-loop with an adjustment frequency of one in each produced file for the reason that this performs the best optimization between the quality of the production of teeth and the number of adjustments. The alternative of the adjustment for each 5 produced files was not considered due two major inconveniences: on one hand, the high amplitude obtained for the control parameter, which does not allow obtaining files with more uniform cut characteristics (higher quality) and, on the other, the possibility of several files be produced (maximum 4) with incorrect teeth depth with no adjustment. In Fig. 15, it can be verified that at the end of the production of 105 files (21 lots of 5), an abrupt decrease of the penetration depth happened which crossed the minimum limit of quality. This particular case was caused by the rupture of the cutting edge of the chisel, which causes the order to stop the machine production from the control system

4. Conclusions

The measurement system used to evaluate the process behavior has been developed and tested. The experimental obtained waveforms suggest that this system is adequate to measure the main parameters involved in the cutting operation. Beside they help to understand the process on itself.

In order to eliminate the mentioned subjectivity factors, the actual all-mechanical system was changed into a mechatronics one, allowing the automatic control of the penetration depth, giving the system the reliability and the flexibility to be adapted for any type of file.

The present research demonstrates that the proposed close-loop control is adequate for adjusting the presser foot and the spring force in order to giving repeatability to the production of the file teeth.

5. References

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