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Method of Selecting a Rational Strategy in Sustainable Friction Drilling

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ABSTRACT

The presented paper contains a description of a new method of determining the optimum feed rate for a waste-free, energy-efficient drilling process being a friction drilling. Previous experience has shown that the energy required to drill a hole by friction drilling is closely correlated with the drilling cycle time. Based on the authors' own experience, the thesis was put forward that the optimum feed rate during the drilling procedure should be variable but smooth. Additional evaluation criteria for the developed method were the drilling cycle time, the maximum values of the axial force and torque, the maximum values of the feed drive and machine spindle drive load, as well as the energy consumption. The test rig was based on a numerically controlled machine tool, equipped with an axial force and torque sensor, and additional dedicated measuring devices for measuring energy consumption. The results of the study indicate the high competitiveness of the developed approach, compared to the feed rate control strategies in a friction drilling cycle known from the literature. The proposed approach for selecting the longitudinal feed rate can quickly gain a significant number of applications. Studies have shown that optimally planned feed rates can reduce energy intensity by up to 47%.

Keywords: friction drilling, optimum feed rate, energy consumption, sustainable machining

INTRODUCTION

Rising energy prices and increasing pressure from environmental protection are forcing industries to implement energy-efficient technologies, including improving the energy efficiency of machining processes, usually less than 30% [1]. The mechanical engineering industry consumes a significant amount of energy, often with low energy efficiency, and causes serious environmental pollution, being one of the main sources of CO_2 emissions [2]. Improvement in this regard is an urgent scientific problem. However, the dominant CNC machine tools today are complex, multi-component and multi-tasking machines, so reducing the energy consumption of a machine tool in the use phase can be difficult [3]. The search for energy savings in manufacturing processes implemented on machine tools is progressing in many directions, through: the use of more efficient drive systems, reducing the extent of machining, monitoring machine tool operation to enable the rational use of auxiliary equipment [4], appropriate selection and dosage of lubricants and coolants necessary for the correct progress of the machining process [5], and through energy-reduction-oriented optimisation of process parameters [6,7]. In order to achieve significant improvements in energy efficiency and environmental performance in industry, it is expedient to obtain real-time REEs for the inputs in use [8]. A complete analysis of the machining process energy characteristics and energy-efficient optimisation of machining parameters using energy consumption models is presented in paper by [2]. This paper also contains an up-to-date study of realised research on the optimisation of energy-efficient machining parameters using experimental design. An accurate model of the energy intensity of machine tools can be the basis for selecting optimal machining process parameters leading to sustainable production [9].

Current trends in product topology favour material-efficient designs combined with energy-efficient and environmentally friendly manufacturing processes. The increasing use of thin-walled components in modern structures entails — in addition to material savings — savings at the operating stage due to their lighter weight. At the same time, it gives designers more freedom to design complex topologies for their structures, increasing their functionality [10]. However, a problem has arisen in providing technological assembly and disassembly for recycling purposes in such structures. This problem has been solved, among other things, by using friction drilling in thin-walled structural components with wall thicknesses of up to 12 mm, extending the effective length of the threaded joint by an average of three times. This technique therefore makes it possible to make more durable connections in machined metal parts of lesser thickness. Friction drilling, also known as thermal drilling or flow drilling, is a method of making hot-formed holes in sheets, tubes and thin-walled sections made of ductile metal alloys, such as all weldable steels, stainless steels, acid-resistant steels, aluminium, copper, brass, bronze, magnetic materials, speciality alloys, non-ferrous alloys. Friction drilling is an environmentally friendly way of making holes. It is the most cost-effective and extremely efficient technique in sheet metal fastening [11]. Additionally, it increases the durability of products by increasing the strength of threaded connections and eliminates electrochemical corrosion due to the use of a single base material. Thanks to this chipless drilling process, no chips enter the hollow sections, avoiding costly and time-consuming cleaning. The heat required to plasticise the material (Fig. 1) is not supplied from outside, but results from the friction between the rotating conical tool and the material.

Friction drilling is a waste-free method, as all the material removed from the hole contributes to the formation of the collar and sleeve on the other side of the hole (Fig. 2). It therefore solves the problems of joining thin-walled structural components in a simple, economical and environmentally safe way. The results of scientific works [12] show that friction drilling, compared to conventional drilling, allows a noticeable reduction in all categories of environmental impact. The lack of need for intensive use of machining emulsions, as in conventional drilling processes, is a key aspect that means a drastic reduction in the environmental footprint. In some cases, trace amounts of lubricant are recommended, mainly to improve surface quality and extend the life of the drill or tapping tool. The above features plus a long tool life of up to 11,000 cycles [13] and a clean workplace allow friction drilling to be counted among the clean technologies supporting sustainability.

Numerous scientific papers published in recent years in the area of friction drilling have mainly dealt with aspects of drilling holes in materials that are difficult to machine, such as stainless steel AISI304 [14], titanium alloys Ti-6Al-4V, Inconel718 [15], austenitic stainless steel AISI 321 [16], C17200 beryllium copper [17], or brittle materials such as A7075-T651 alloy [18]. However, the application of the friction drilling technique for hard-to-machine alloys is limited due to its small range. From the point of view of the environmental impact of the manufacturing process, high-volume and mass production is important. On a large scale, friction drilling

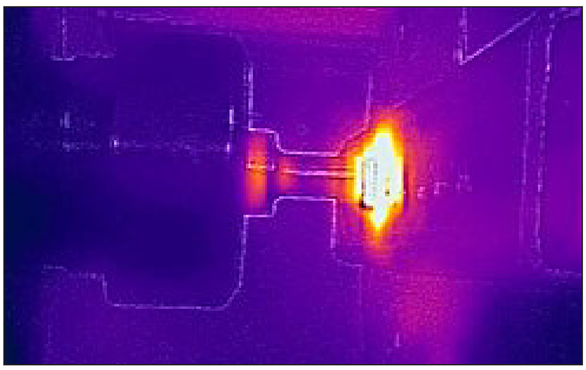


Fig 1. Friction drilling monitoring with an infrared camera

Fig 2. Collar and bushing of friction drilled hole

processes are used for typical soft structural steels and aluminium alloys.

To date, scientific work in the field of friction drilling has focused on investigating the feasibility of using this technique and evaluating the results obtained. Currently, the influence of technological parameters on heat generation and deformation during friction drilling, which determine the quality of the joint, is well studied [19]. Most researchers use classical methods of analysis of variance (ANOVA), to study the influence of process parameters on the effects of the friction drilling process, and the Taguchi method for searching for optimal solutions [20]. Another group of research papers deals with the construction of friction drilling process models and the optimisation of process parameters through virtual testing [21]. The main objective of this research is to optimise tool geometry, drill speed and axial feed to maximise bushing height and thickness for different materials, different material thicknesses [22,23] and bushing surface roughness. The same issue by unconventional methods using artificial neural networks and evolutionary algorithms was optimised in the works of [24,25], where an integrated ANN-SA approach was used. In the work of [26], an integrated adaptive network-based fuzzy inference system (ANFIS) and a genetic algorithm were used to determine the optimal value of the surface roughness parameter obtained by friction drilling. In these studies, a constant, relatively small feed rate, not exceeding 200 mm/min., is assumed during the drilling cycle. Only in [27] was a significantly higher feed rate of 500 mm/min tested, and it was found to shorten the length of the sleeve compared to a feed rate of 100 mm/min. In the work of [14], a feed rate of 60 mm/min was found to be optimal for a Ø9.2 mm drill bit, while also stating that energy consumption during machining decreases when the axial force decreases. It should be noted, however, that a reduction in feed rate increases the drilling cycle significantly and that cycle time is critical to total energy consumption. A higher feed rate ensures minimum energy consumption also in turning processes, although it leads to higher surface roughness [6]. Although the cognitive value of the completed research work is high, its practical usefulness is limited, as each production station and each production process has its own very specific characteristics in terms of energy requirements. The energy characteristics can vary considerably for different types of CNC machine tools, due to the complexity of the machine tool design. Hence the need to focus on the development of effective methods to rationalise the process parameters in a short period of time under specific shop floor conditions.

The authors set out to fill one of the research gaps that existed in this area of knowledge, namely the selection of the optimum feed rate during the friction drilling cycle, in terms of productivity and energy efficiency. The efficiency of the drilling process is primarily determined by the right process parameters. While the spindle speed has a decisive influence on the quality of the formed sleeve, the axial feed rate determines the drilling cycle time. Energy consumption is affected by both parameters. Experience shows that the feed rate should be variable at successive stages of the cycle. For this reason, drill bit manufacturers propose to their customers to use a step-variable feed. As shown in the paper by [28], such a solution is not optimal, as other strategies for changing the feed rate, such as linear variable feed or adaptive AC on-line feed control, give significantly better results in terms of cycle time and, in addition, reduced energy consumption. The innovative adaptive approach to feed control during a friction drilling cycle presented in this work has several undoubted advantages, but requires a suitable controller and a high level of competence and experience from the potential user, hence it is difficult to expect it to be more widely popularised. The use of a continuously variable feed rate, makes the problem much more complex. Theoretical process models developed for a constant feed rate are useless when using a continuously variable feed rate. The use of widely varying feed rates in one short friction drilling cycle raises a new problem, i.e. how to regulate the feed rate to avoid sudden jerks of the drive, detrimental to its durability. Rapid changes in feed rate during the drilling cycle cause alternating accelerations and decelerations of the axial movement. These phenomena are difficult to control automatically and additionally generate adverse acoustic effects.

Hence, this work proposes an alternative, recursive method for feed rate selection in the friction drilling process. In order to achieve a relatively smooth feed rate, the drilling cycle was divided into a number of elementary sections and an individual feed rate value was set at the end of each section. The problem to be solved was that it was very labour-intensive to find the optimal, and in this case very subjective, feed rate values when they would be set manually by the user. Therefore, the authors of this thesis decided to automate this task by developing an appropriately configured spreadsheet, within which smoothing functions were used to avoid step changes in the feed rate. Cycle time, energy intensity and the other quantities considered are in this case at a similar level to the adaptive method. The advantage of the recursive method over the adaptive method lies in the smoothness of the feed rate control and the automation of the feed rate selection process. In the opinion of the authors this opens the possibility of its wider dissemination, as it does not require much experience and high competence of the potential user.

EXPERIMENTAL SETUP

Metering systems for electricity consumption in generation processes are most often built on dedicated energy meters and programmable logic controllers (PLCs). These allow REE measurement by quantifying signals at high sampling frequencies. An example is, presented in [4], a measurement system based on the Siemens Sentron PAC4200 advanced network parameter analyser. In the work [29], the power consumption of a machine tool and its spindle system was measured using an HC33C3 power sensor. The developed dedicated machine tool energy efficiency monitoring system was used to demonstrate the REE. The configuration of the experimental power and energy acquisition system was also presented in the work [30]. The work [31] presents an approach for determining the relevant KPIs, in the context of energy efficiency and productivity of machining processes, based on real-time interpretation of sensor and machine control data recorded in a SCADA system.

In this work, the test rig (Fig. 3) was based on a CNC universal lathe, equipped with a SINUMERIK 810D numerical control system, with an additional external digital I/O panel to control the necessary synchronous actions. The tool is integrated into the machine spindle using an ER25 collet chuck. The workpiece was square tubing with wall thickness of 2 mm, made from S235JRH EN 10219 carbon steel. Each time, prior to the next drilling cycle, the workpiece was repositioned to ensure centricity of the drill axis and the force gauge axis. The workpiece holding fixture was integrated with a Kistler 9272A piezoelectric force gauge, allowing axial force and torque to be measured during the drilling procedure. The company's software allowed the acquisition, visualisation and archiving of the measured values.

In order to be able to measure the electricity consumed, a prototype measurement system was made, based on an Eastor SDM630 bidirectional electricity meter, a Siemens S7-1200 programmable logic controller, together with a CB1241 communication module. The PLC used has the ability to record internal variables for each cycle of the programming loop using the Traces tool included in the TIA Portal programming environment. The exchange of information between the counter and the controller was realised via the RS485 bus using the Modbus RTU protocol. The controller reads the counter register containing the instantaneous three-phase power that the machine tool loads into the mains. For each reading, a timestamp with nanosecond accuracy and the values of the recorded variables are stored. Recording is carried out in hardware by the controller's processor to its internal memory. When the PLC's processor memory is full or the logging stops, the data is sent to a computer from which it can be downloaded in CSV text format. The synchronous actions used in the NC programme allowed the energy meter reading and the torque and force recorded by the force gauge to be synchronised.

RECURSIVE FEED SETTING ALGORITHM

The recursive algorithm is a cyclic algorithm in which, each time, the results from the previous iterative loop provide input to the next loop. The condition that interrupts a recursive algorithm is the point at which the execution of subsequent iterative loops does not produce a significant change in the result. In the case of calculations implemented using a spreadsheet, recursive calculations mean that the spreadsheet is recalculated each time in each subsequent iterative loop (Fig. 4). The iterative loop of the method in question has a physical part, executed on the NC machine tool, and a computational part executed on a PC. A pre-generated subroutine is run on the machine tool, containing the feed rate declaration in the form of an array. During the drilling cycle, information is recorded by means of synchronous actions, every specified distance, to evaluate the speed of the plunge motion and the load on the drives. The suitably formatted results, in the form

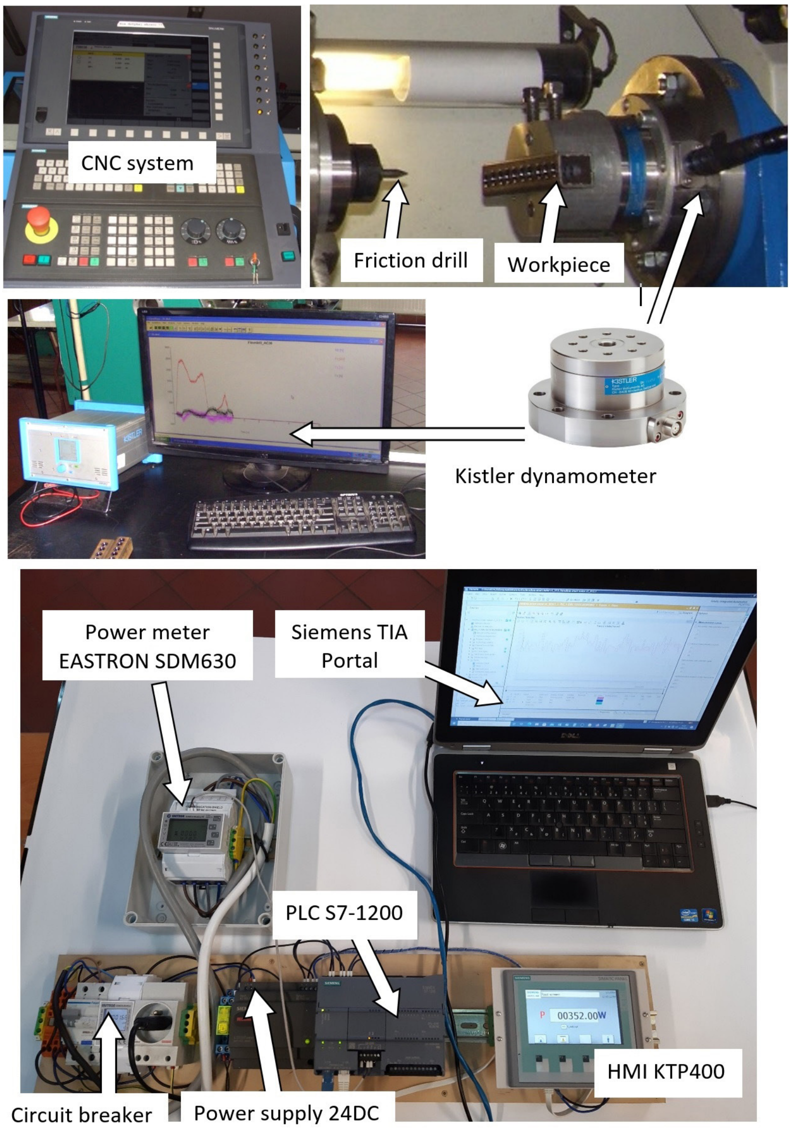


Fig. 3. Test rig for measuring energy consumption during friction drilling

of a text file saved at the end of the drilling cycle, are in turn the input to the calculation part, which is carried out outside the machine tool in a spreadsheet. The main calculation spreadsheet is coupled to an auxiliary spreadsheet, whose text-formatted record is a subroutine containing the new feed values, which closes the iterative loop. Theoretically, it is possible to implement all calculations in the machine tool's numerical control system. However, this approach deprives the user of the possibility of tracking the convergence of the algorithm, using graphical diagrams.

Before starting the procedure of determining the feed rate, it is necessary to determine the recommended load values for the main drive and the feed drive. These are based on recommendations from the tool manufacturer, the power of the drives and the user's own experience. As shown in the paper by [28], there is a very clear correlation between the force and torque recorded by the actuator and the load of the respective drives. It is important to be aware that the maximum load on the working spindle drive occurs during the acceleration of the spindle to the programmed RPM value. Once this is reached, the main drive at idle uses only a few per cent of the nominal power. Therefore, with a force gauge, it is possible to determine the percentage load values of the individual drives that do not overload the friction drill on the basis of the axial force and torque readings.

Friction drills are available in two lengths, short and long. The correct length variety of drill is selected according to the thickness of the material and the function of the hole. Short drills are used for threaded holes, where the shape of the tip of the drilled sleeve is slightly conical,

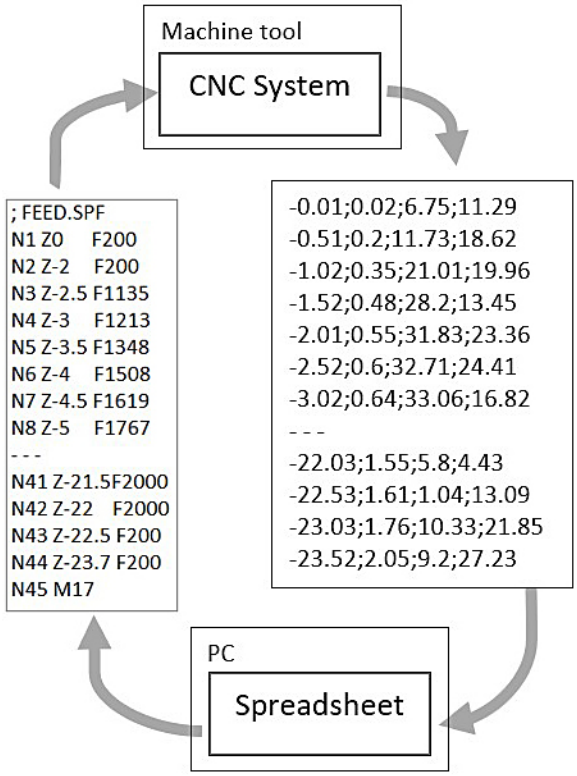


Fig. 4. Data exchange in a recursive loop

which improves the strength of the joint. The short drill also reduces the flaking effect of the hole tip. Long drills are used for holes where a regular through-hole cylinder is required along the entire length of the hole. The distance the drill covers during the drilling cycle can therefore vary greatly, depending on the type of drill, its diameter and the thickness of the plate. Hence, two different densities of drive load readings were adopted in the study. For short runs of 0.25 mm, and for longer runs of 0.5 mm.

The procedure starts with a friction drilling test on the NC machine tool, with the feed rates assumed to be constant or recommended by the drill manufacturer. The NC program used, by means of synchronous actions, stores the following data each time a fixed distance is covered: the time since the drill made contact with the material, the load on the main drive performing the rotary motion and the load on the axial motion drive. At the end of the cycle, this data is saved in tabular form on a file in a spreadsheet-acceptable format. The calculations in the spreadsheet are carried out in several steps:

For the i-th row of the data table, the relative drive load is calculated as:

$$L^C_{r\,i} = L^C_{a\,i} / L^C_{set} \tag{1}$$

$$L^Z_{r\,i} = L^Z_{a\,i} / L^Z_{set} \tag{2}$$

An example of the distribution of relative load values, for the preferred values and is illustrated in Figure 5. The relatively large spread

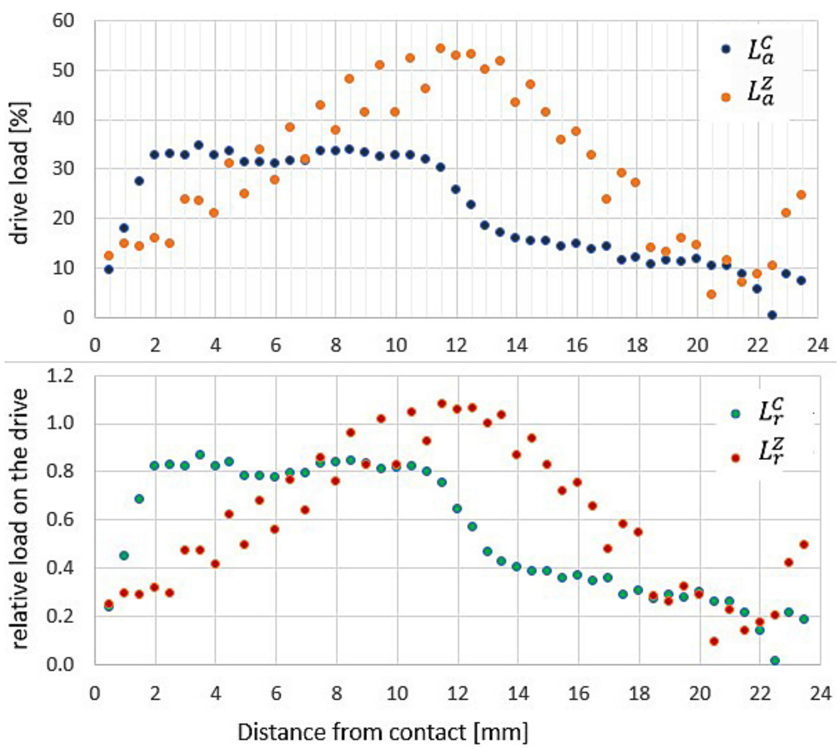


Fig. 5. Example of a spindle drive load and feed drive load distribution

of readings for the spindle drive is due to the oscillation of the reading of this value. Averaging the readings at this stage is not advisable because, as tests have shown, it degrades the convergence of the proposed method. It can be observed that some readings of the C axis load exceed the preferred 50%. This indicates the need to reduce the feed rate on this section.

In the second step, for the i-th row we calculate the feed rate correction factor Cf, individually for each drive according to relations (3) and (4). An example of the distribution of correction factor values for the data in Figure 5, is illustrated in Figure 6. Correction factor values greater than 1 indicate the possibility of increasing the feed rate at a given point. Values less than 1 indicate the need to decrease the feed rate at that point.

$$Cf_i^C = 2\text{-}L_{r\,i}^C \tag{3}$$

$$Cf_i^Z = 2\text{-}L_{r\,i}^Z \tag{4}$$

In the next step, the suggested feed rate values are determined, taking into account the previous distribution of feed rate values F_p, used in the last test, and the correction factors for each drive, as in equations (5) and (6). If the calculated value exceeds the user-allowed feed rate F_{max}, the value of F_{max} is adopted.

$$F_{n\,i}^C = min\begin{cases} Cf_i^C \cdot F_{p\,i} \\ F_{max} \end{cases} \tag{5}$$

$$F_{n\,i}^Z = min\begin{cases} Cf_i^Z \cdot F_{p\,i} \\ F_{max} \end{cases} \tag{6}$$

In the next step, trend lines are determined from the feed distribution, individually for both drives. A sixth-degree polynomial was used to determine the trend line. For short drills, a polynomial of the fifth degree can also be used, as the shape of the trend line for the calculated feed rate is smoother. An example of the determined trend lines for a Ø8 drill bit is shown in Figure 7.

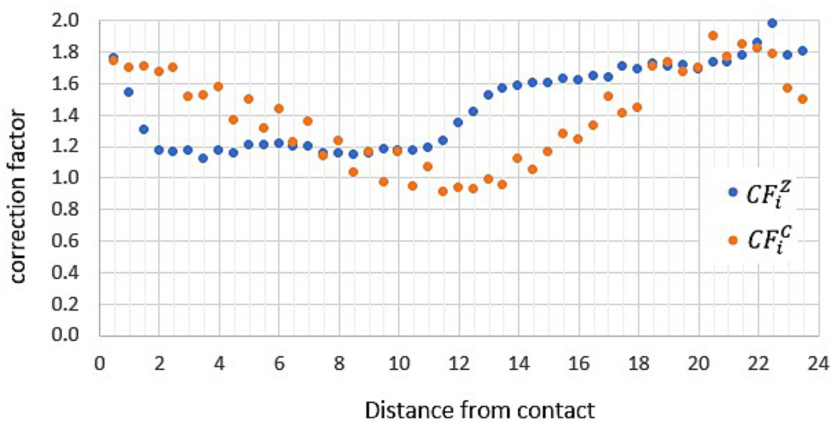


Fig. 6. Formation of the correction factor for spindle drive (C) and feed rate (Z)

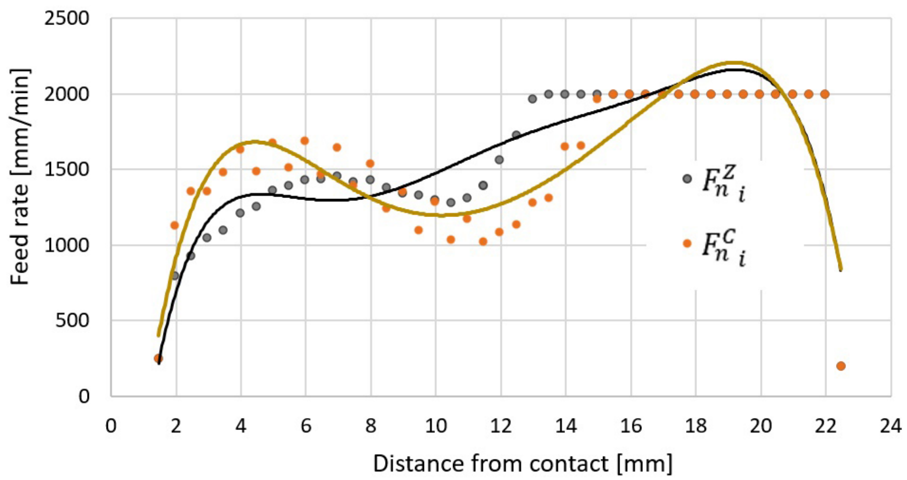


Fig. 7. Example of calculated trend lines

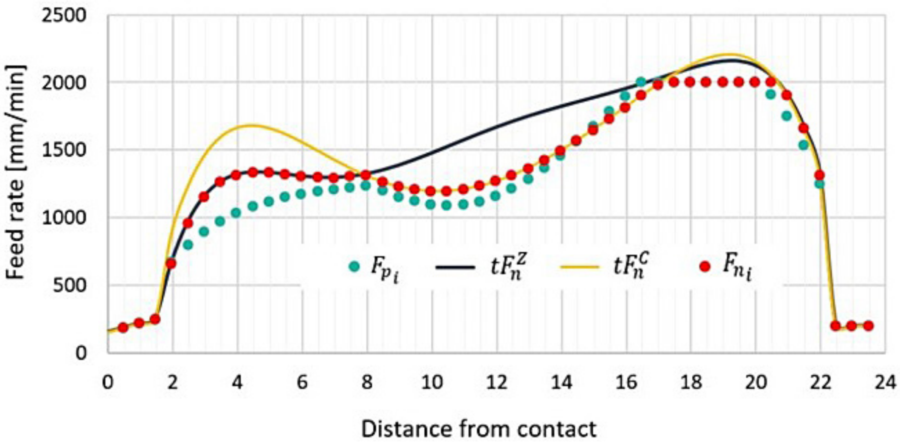


Fig. 8. Example of determining a feed table in the next F_n test

In the last step of the iteration loop, a new feed rate table F_n is determined from the read-out coefficients of the polynomial trend line. The feed rate values at the following points are determined (7) as the minimum of three values: the suggested value resulting from the main drive load, the suggested value resulting from the axial drive load and the maximum user-specified feed rate value F_{max}. In the case of the trial presented in Figure 8, this value was 2 m/min. Successive feed rates in the table were determined for short drills at 0.25 mm increments and for long drills at 0.5 mm increments. The determined new feed rate table is transmitted to the CNC system, where it is substituted for the existing one.

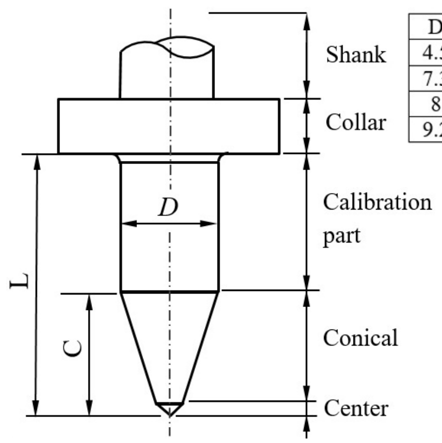
$$F_{n_i} = min \begin{cases} tF_{n\ i}^{C} \\ tF_{n\ i}^{Z} \\ F_{max} \end{cases} \tag{7}$$

The above recursive loop is executed several times. The condition for its interruption is stabilisation of the drilling cycle time. The number and rate of change of the feed rate values in successive iterations depends on the value of the preset feed rate and the determination of the level of the preferred drive load values. The latter are in turn determined by taking into account the diameter of the drill bit and the power of the main drive and axial drive of the machine tool used.

EXPERIMENTAL RESULTS

Due to the large number of experiments carried out, only selected examples of the results achieved are presented below. As an example of the process for a short drill, the results for a Ø4.5 drill bit are presented, while a Ø8 drill bit represents the cycle for a long drill. Figure 9 shows the drill outline and the basic dimensions of the working part for Ø4.5 (M5), 7.3(M8), 9.2(M10) and Ø8 drill bits. Friction drill bits are made of carbide with optimum gradation and highest temperature resistance combined with high hardness.

Figure 10 shows the development of the feed rate in successive iterative steps for a Ø8 mm long drill bit. The tests were performed on a profile made of ordinary structural steel with a wall thickness of 2.5 mm. The set loads for the main drive (C axis) and the feed drive (Z axis) were 50% and 40% of their maximum load, respectively. In the first drilling section, down to a depth of 1.5 mm, a continuously variable feed rate of 150–200 mm/min was used, due to the need to heat up the drill bit and plasticise the material. Increasing the feed rate in this section would lead to adverse phenomena in the form of increased axial



D	L	C
4.5	9.1	5
7.3	17.6	9.5
8	24.5	10
9.2	22.2	12

Fig. 9. Shape and basic dimensions of the drills used in the tests

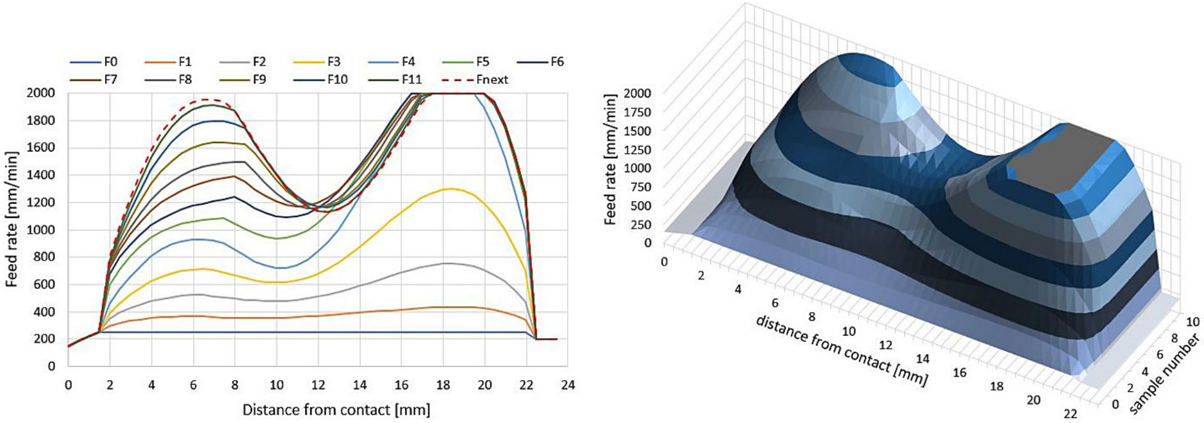


Fig. 10. Formation of the feed rate in successive tests of the recurrent method for a long Ø8 drill bit

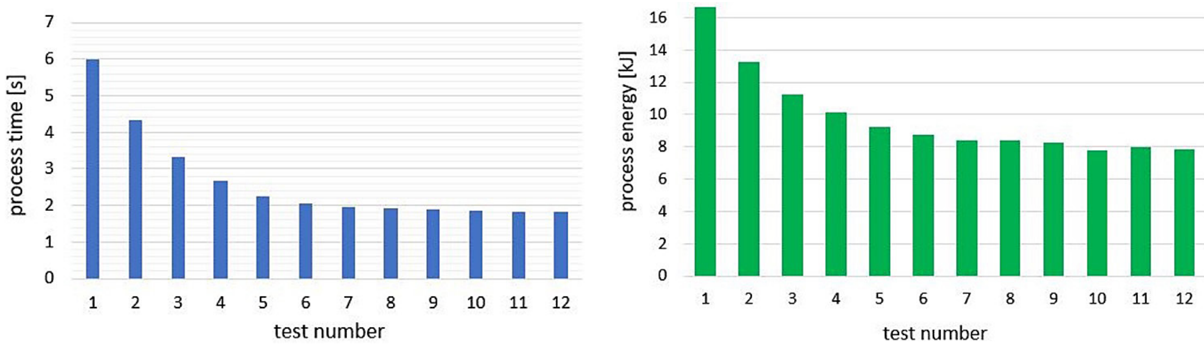


Fig. 11. Process time and energy demand in successive steps of the recursive method for a Ø8 drill bit

force and a drastic reduction in drill life or even catastrophic wear. In the first test, a constant feed rate of 200 mm/min was used. In the following 2 steps, relatively small changes in the feed rate can be observed, due to its insignificant current value. Steps 3 and 4 produce the largest changes. However, once the permissible maximum values are reached, the feed rate changes begin to stabilise. The feed rate differences between the last, 11th test and the next run generated are small enough that they will not cause a significant change in the duration of the drilling cycle. As can be observed in the spatial graph, the widest area of maximum feed rate occurred in test 6. Thereafter, it was reduced, which, however, did not result in an increase in cycle time, but had a positive effect on the uniformity of the feed drive.

Figure 11 shows the development of the feed rate in successive iterative steps for a Ø4.5 mm short drill bit. The tests were carried out for the same material and wall thickness as before. The set loads for the main drive (C axis) and the feed

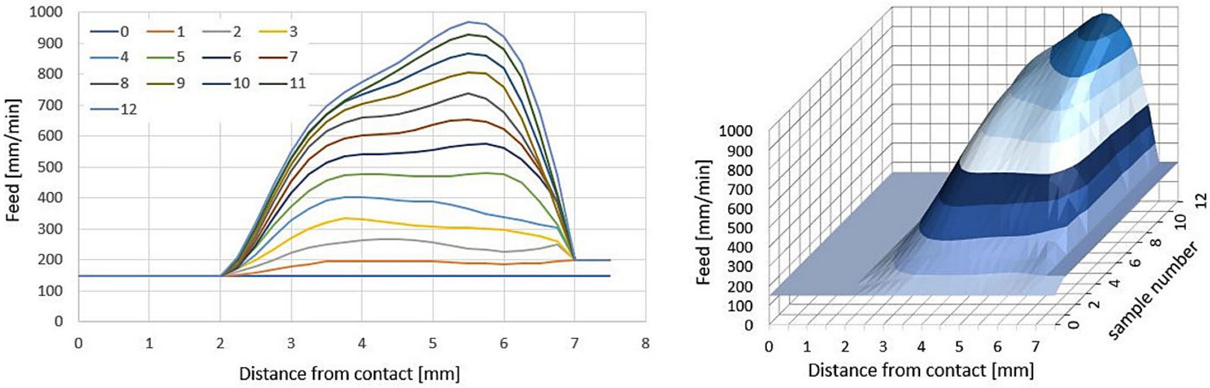


Fig. 12. Formation of the feed rate in successive tests of the recurrent method for a short Ø4.5 drill bit

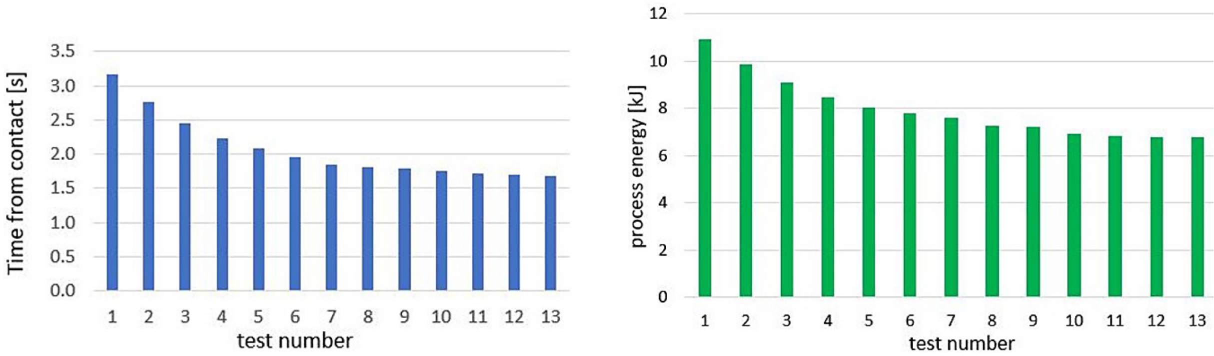


Fig. 13. Drilling process time and power consumption in successive tests for a short Ø4.5 mm drill bit

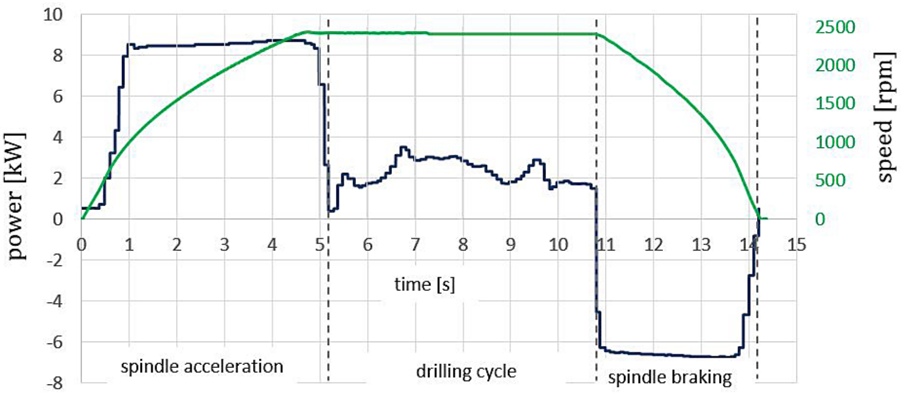


Fig. 14. Power consumption in successive phases of the friction drilling process

drive (Z axis) were 40% and 25% of their maximum load, respectively. The maximum feed rate, as in the previous case, was 2 m/min. A constant feed rate of 150 mm/min was used for the first trial. As could be assumed, the graphs representing the feed rate in subsequent tests were simplified, relative to the long drill. The level of maximum feed rate was not reached in this case. The experiments were stopped after 13 tests, as the drilling cycle time stabilised at 2.4 s (Fig. 14). The difference in drilling cycle time is due to the possibility of using higher feed rates for a Ø8 drill bit.

Figure 14 shows the typical power requirement of a friction drilling cycle. The entire process can be divided into three phases. In the first, which includes spindle start-up, there is by far the highest energy demand, due to the need for the spindle to reach high speeds. In the second

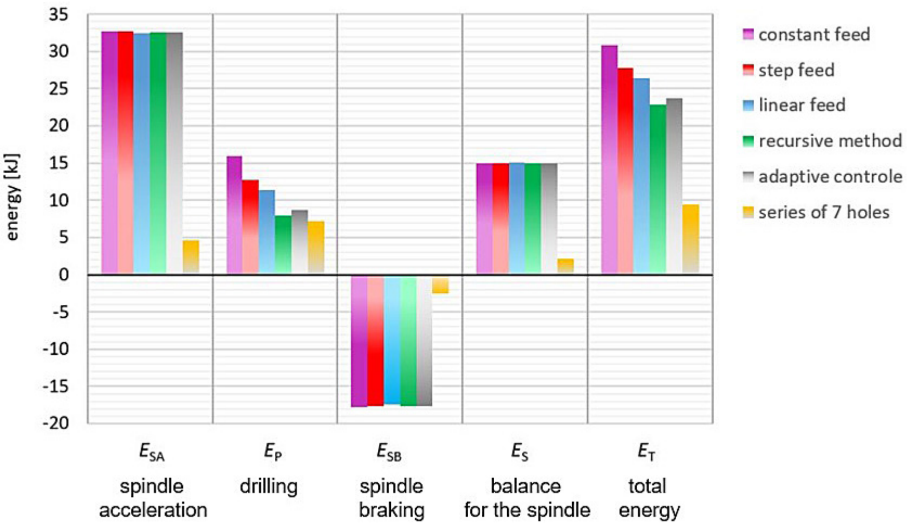


Fig. 15. Analysis of energy consumption for different feed strategies

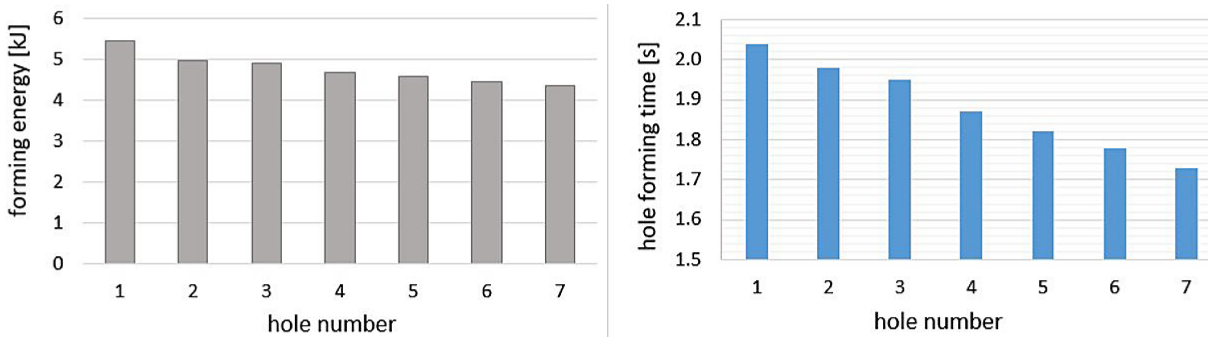


Fig. 16. Energy consumption and hole formation time for a series of 7 consecutively drilled Ø8 holes with active adaptive control

phase of hole formation, the demand is generally much lower and variable, due to the constantly changing conditions of the hole formation and its flange. In the third phase, involving spindle braking, power is recovered, hence its negative value. As shown in Figure 15, the total energy demand of the spindle $E_S = E_{SA}+E_{SB}$ is constant, regardless of the feed control strategy used. Only in a multiple-hole drilling cycle, without spindle stopping, with active adaptive control, the average per-hole energy demand is, of course, considerably lower. However, under production conditions, it is not always possible to drill an uninterrupted sequence of holes. For a process involving the formation of a single hole, the best result, i.e. the lowest process energy E_P and total energy E_T, was obtained when using the recursive feed selection method.

It is worth noting that the average energy requirement for an n-hole drilling sequence is lower than for a single hole drilling with active adaptive control. This is due to the fact that the drill bit is at a high temperature after the first hole is drilled, which blocks the heat flow for subsequent holes, thereby facilitating plasticisation of the material. Figure 16 illustrates the significant reduction in energy demand when forming subsequent holes with active adaptive control. In this case, energy lost to idling movements is not included.

CONCLUSIONS

The work presented here presents the results of experiments carried out in the search for the optimum feed rate in the friction drilling process, from the point of view of process efficiency and energy consumption during its execution. In this way, it fills a significant research gap, as the work presented in the scientific literature assumed a constant, relatively low feed rate during the cycle. Up to now, the optimisation of the parameters of a friction drilling process implemented under mass production conditions often required lengthy and therefore costly tests, often outsourced to the manufacturer of the friction drilling tools or a specialised scientific research unit. Therefore, a fast recursive method, universal for different drill bits and material thicknesses, was developed to generate a recommended feed rate based on 10–12 tests. A series of tests were carried out for different variations of the method, allowing the most favourable approach to be selected. The method is easy to apply, requiring no additional apparatus, advanced software, extensive experience or skills from the user. It is applicable to various types of NC machine tools. There were no visible defects in the formed sleeve or shortening of its length, compared to holes made with constant feed parameters. The tool life should not decrease, as it depends mainly on the temperature of the drill, which in turn depends mainly on the speed of the drill, which in the tests carried out was constant and in accordance with the tool manufacturer's recommendations.

The tests carried out indicate that the use of an optimised, smoothly continuously variable feed rate offers great potential for reducing the energy intensity of the friction drilling process. Particularly large savings can be achieved by drilling a series of holes consecutively, at short intervals, with the same drill bit. Additional benefits in this case result from the use of an adaptive feed control strategy that adjusts the feed rate to the current load on the machine tool drives. Due to the constant expansion of the area of application of friction drilling processes, the energy savings achieved, at the level of several tens of per cent, can make a contribution to sustainability.

The developed optimisation approach has potential applicability to other repetitive manufacturing processes. A number of arguments are presented in this thesis, such as: increased process efficiency, resulting in better utilisation of personnel and equipment resources, broader application of the method, which favours a reduction in the use of construction and tooling materials, an eco-friendly process flow, a reduced environmental footprint and, above all, reduced energy consumption. These benefits allow us to conclude that friction drilling processes fully meet sustainability expectations.

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