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Chip control system for monitoring the breaking of chips and elimination of continuous chips in rough turning

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1. Introduction

All industrial activity must be productive. The search for ways to improve productivity is an ongoing pursuit. Measures that were sufficient for improving productivity a year ago are no longer adequate. The productivity of part manufacture in the metal cutting industries has been improved mainly by increasing automation in handling the work piece outside the machine tool. The processes themselves and their control also need to be developed – especially by making the cutting processes more efficient in terms of systems technology.

The formation of chips plays a key role in making the cutting process run smoothly. A continuous chip is formed when the chip does not break off. In normal cutting conditions, the chip breaks off on its own, against the tool or work piece. Discontinuous chips are a prerequisite for safe and productive machining. A continuous chip is a long metal string that becomes tangled or wraps around the cutting tool or around the turning work piece. A continuous chip may damage the machine tool if it forms a large enough tangle around the cutting tool.

A number of models have been generated to forecast the breaking of the chip [1]. They are not, however, directly applicable to the adaptive control of machining. Consequently, research on the form of the chip during machining [2, 3] is important. In some researches the shape, length and colour of the chips has been inspected visually during cutting tests [4]. Efforts have been made to forecast chip formation and control it during machining especially in unmanned production [5], in which continuous chips mean interruptions in production. Appropriate chip formation is necessary in order for the cutting to proceed without obstacles.

Monitoring the length of chips during machining may focus on measuring the length of the chip (e.g. with machine vision) or detecting the breaking of the chip with signals such as acoustic emission. Earlier studies [6] indicate that a force sensor attached to the tool holder can be used to define the breaking frequency of chips. However, attaching such sensors to the tool holder is problematic since tools are changed continuously. Several studies have shown that a continuous chip can also be detected with acoustic emission signals [7-9]. The studies have demonstrated that sources for AE signals in metal cutting include, e.g. the breaking of the tool or the chip [7, 9].

Microphone signals detect continuous chips only randomly, and therefore, their use as the only detection method is not justified [10].

1.1. Research objective

This study developed a chip control system for rough turning that monitors the breaking of chips, estimates the length of the chips and eliminates continuous chips if those are formed. Chip breaking was identified with acoustic emission signals during machining. The objective was to create a system that could break chips off (eliminate them) even when increasing the feed will no longer induce the breaking of the chip.

2. Created control system

The system was built around the NC turning machine Doosan Daewoo Puma 2500Y at Lappeenranta University of Technology. The turning machine included Fanuc 18i-TB control. The prototype system included a PC equipped with the Windows XP operating system and the National Instruments data acquisition board PCI-6251, and another PC with the GNU/Linux Debian 3 operating system and a Fire wire port.

2.1. Description of the system

The measurement system built in connection with this study for detecting continuous chips uses an acoustic emission sensor. Previous experiments include, e.g. two acceleration sensors (vertical and horizontal), a microphone and the measurement of electric power consumed by the spindle and feed motor. These practical tests indicated, however, that acoustic emission was the most reliable method for detecting continuous chips.

Acoustic emission was measured with an acoustic emission sensor (SEA) and amplifier (SEP) manufactured and used by Nordmann GmbH as a part of their machining control equipment. The AE sensor was attached to the tool holder with screws (Fig. 1), and was positioned as close to the tool as possible, taking into account usability and protection-related restrictions. The cables of the sensors are protected with steel tubes, and in addition, the sensors in the tool holder are protected with a metallic shell during cutting.

The measurement area of the acoustic emission sensor extends to approximately 1 MHz according to the manufacturer. The high-frequency signal (typically > 100 kHz) is modified in the amplifier (SEP), which allows the high-frequency vibration – the acoustic emission – to be detected at lower frequency bands.

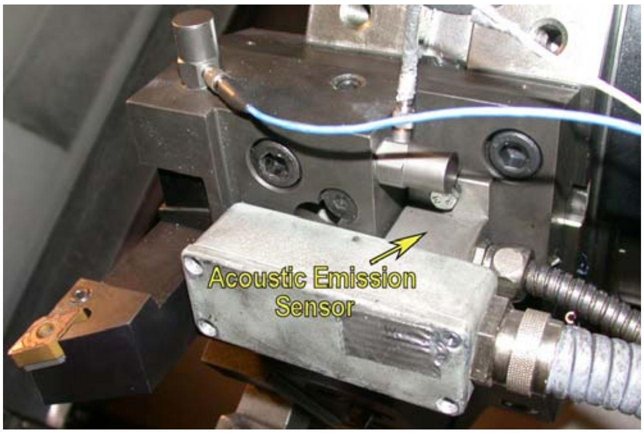

Fig. 1 Positioning of the sensor on the tool holder of the turning machine turret

The analogy signals received from the sensors are transmitted to one of the computers with the data acquisition board. The data acquisition board was a multichannel PCI-6251 model manufactured by National Instruments and attached to the PCI. The A/D conversion resolution of the data acquisition board is 16 bits, and the multichannel composite maximum sampling rate is 1 MS/s

The data from the data acquisition board is captured using National Instruments LabVIEW software suite. The program allows creating a measurement interface with which the captured measurements can be monitored in real time, and the sampling frequency can be changed. As a rule, a frequency of 20 kS/s (20 kHz) was used in the experiments. Thus for instance the information received through the AE sensor is read and saved on the hard drive at the rate of 20,000 samples per second. In addition the MathWorks Data Acquisition Toolbox (DAT) plug-in for MATLAB was installed on the computer. Consequently, the data from the data acquisition board could also be handled directly to MATLAB and Simulink software without using a separate data acquisition suite.

2.2. Signal processing

The purpose of the chip length estimator is to enable continuous real time chip length control so that the chip length can be set to any acceptable value. In such case, the recognition of continuous chips does not suffice, but the estimator should output a continuous value. Inasaki [7] has used an acoustic emission (AE) sensor to monitor a cutting process. The AE signal was analyzed in the time and frequency domains, and different indicators such as kurtosis and standard deviations were calculated. The calculated values were fed to a neural network, which classified the samples into continuous or discontinuous ones. Andreassen [6] has applied a feed force measurement to automatic detection of chip breakage; he uses power spectrum peak features to detect chip length.

The chip break initiates a stress wave that propagates in the tool and the turret. The AE sensor measures these stress waves that have a very high, material-dependent frequency (hundreads of kilohertz). By taking an envelope of the gathered signal and measuring the repetition frequency of the bursts, the time interval between the chip breaks can be estimated. The standard deviation of chip length can be relatively large, often half of the mean length. For example, using the cutting speed of 150 m/min, a 10 mm chip mean length with a 5 mm deviation produce a 270 Hz center frequency with a bandwidth of about 270 Hz. Correspondingly, a 10 cm mean chip length with a 5 cm deviation would produce a 27 Hz center frequency with a 27 Hz bandwidth. Therefore, the chip length is not estimated solely from the frequency peak amplitudes, but the developed algorithm searches for frequency ranges that have a high energy content compared to their neighbourhoods.

The chip length estimate is used as feedback in the feed control. The continuous chip should be recognized in a few seconds for the control. Therefore, a long average time is not possible. The proposed method calculates chip length from the power spectrum of the envelope of the AE signal. The power spectrum is formed using the Welch estimate from a 1.6 second sample with four overlapping sections to attenuate interference and noise. However, the power spectrum obtained still contains many narrowband frequency peaks that are filtered out by a median filter. The baseline of the spectrum plot is a monotonically decreasing curve. In order to find areas where the energy content is higher than in its neighbourhood (knobs), the baseline is removed from the spectrum (the baseline value is subtracted from the spectrum value of a corresponding frequency). In this, the baseline is removed by using ray casting. The spectrum obtained is divided into narrow frequency bands, and the highest peaks in all bands are selected. The energy of the knob containing any selected peak is calculated. Four knobs of the highest energy are selected as candidates for the repetition frequency of chip breakage. The ratio of the energy of the knob to the total energy of the spectrum is calculated. These four candidates and their energies and energy ratios are returned to the decision-making machine. In Fig. 2 the chip length detection procedure is illustrated. The three peaks near 300 Hz show the same knob with high energy, and the chip length is calculated from the knob including these frequencies.

The chip length estimator algorithm, according to tests with hundreds of samples, recognizes the chip length very accurately. However, the detection fails occasionally when the chip is long or continuous, as can be seen in Fig. 3 that illustrates detection of chip length with 30 consecutive data samples is illustrated. The observer has approximated the chip length visually without any measurement devices. The continuous chip is plotted as 75 mm. In the case of a continuous chip, the estimator finds the high energy frequency range at low frequencies corresponding to a long chip (> 50 mm). The estimator fails in the recognizing a continuous chip with samples 28 and 29, but recognizes the situation in the next sample 30.

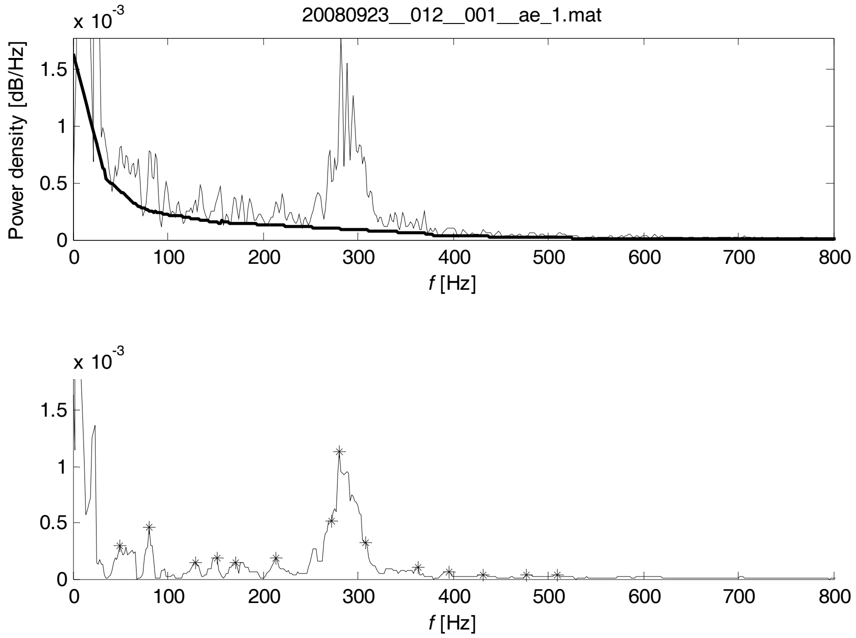

Fig. 2 Detection of chip breakage. In the upper figure, the power spectrum of the enveloped AE signal is presented with the calculated baseline of the spectrum. In the lower figure, the filtered baseline-removed spectrum is illustrated. The markers show the selected frequency peaks

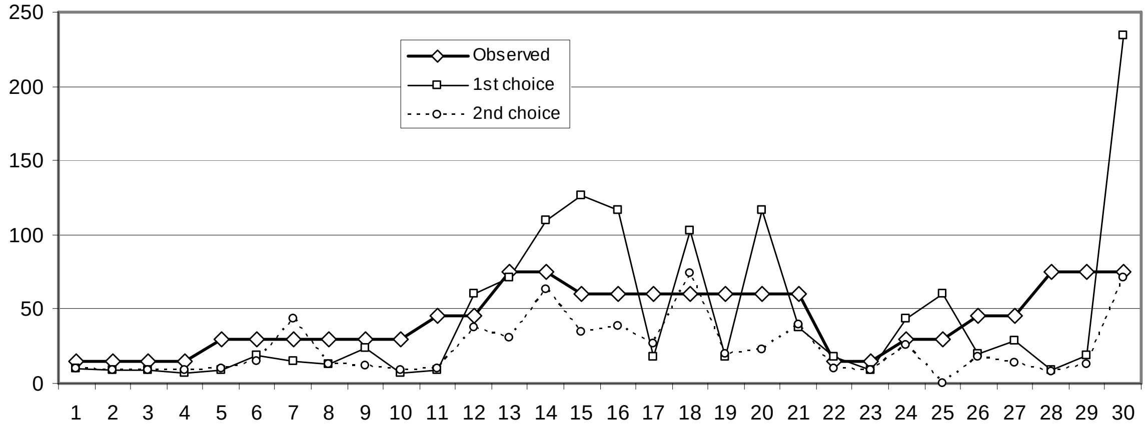

Fig. 3 Detection of chip length with 30 consecutive data samples. The thick curve illustrates the human observer's rough approximation for the chip length in millimetres with the exception that value 75 refers to a continuous chip. The other two curves are the chip length estimates given by the estimator algorithm ranked by energy ratio

2.3. Functionality of the software

The system detects continuous chips based on acoustic emission bursts generated when the chip breaks. Even though the detection of individual bursts may be difficult, examining measurement data collected over a longer time span in the frequency plane allows drawing accurate conclusions on chip length and, to some extent, also the quality of the break. When chips break at even frequencies, the burst generated by the breakage can be detected as a rise in the energy levels of acoustic emission frequency components of the matching frequencies, as described in section 2.2.

The information on the breakage of the chip is entered into the inference system, which also takes into account other possible machining-related observations from the sensors and aims to match the data collected from the turning machine with data on different cutting quality indicators entered into the system. Based on the data collected, on values calculated on the quality of the machining, and on the power consumption of the lathe turning machine, the system modifies the cutting values as needed. The inference system is based on fuzzy logic [11, 12] and can handle a number of demanding problems related to cutting speed and feed simultaneously. The inference system recommends adjustments to the cutting values as seven fuzzy sets: *negative big* (NB), *negative medium* (NM), *negative small* (NS), *zero* (ZE), *positive small* (PS), *positive medium* (PM), and *positive big* (PB). Since fuzzy logic deals with uncertainties, it is possible that more than one of these values are applicable at the same time. The final adjustment is calculated by projecting the geometric centroid of the area covered by the fuzzy sets or the "center of mass" of the adjustment recommendations onto the axis of the value being adjusted (centroid of area method).

The system also interprets long, yet breaking chips as an error in cutting and attempts to increase the feed any time such chips occur. In this case, how much the feed is increased depends on the length of the chip. A very long chip is interpreted as a continuous chip because the identification method applied cannot distinguish between the two cases.

If continuous chips occur, the feed is stopped for a moment, after which a greater feed defined by the inference system is adopted. The feed is stopped because previous tests have indicated that simply increasing the feed during machining does not induce chip breakage. Instead, the feed must be stopped and restarted at a higher rate. This is done also when the system is not quite sure that the chip is continuous, but it is long enough for the change in feed to be PB, i.e. “higher than PM”, due to problems in differentiating between a continuous chip and simply a long one.

The software controlling the system is modular, and detection modules can be added to or removed from it. However, all possible scenarios were not explored when testing the prototype. The idea is to be able to add other machining control functions to the system in addition to detecting chip breakage and cutting off chips.

The control mechanism is based on communication between the software and the turning machine control (FOCAS application programming interface in Fanuc control). The software constantly monitors the cutting values of the turning machine with the help of a data transmission link. When they differ from the desired cutting values programmed into the system, the software calculates the difference between the actual cutting values and the desired values. This difference is entered into the memory of the CNC control, and the machine tool carries out the desired changes. When the system is active, the desired control setting takes over the function of the override switches. Correspondingly, the continuous chip is broken with a brief moment of zero feed input, which brings the feed to a halt. Shortly, a higher feed is adopted. In the prototype system, the fuzzy groups *small*, *medium* and *big* correspond to an approximate change of 5, 10, or 15 percent in the control value, respectively. The change can be either negative or positive, depending on the subgroup, and the subgroup *zero* maintains the prevailing feed.

The shortest cutting time needed to cut a continuous chip could not be determined because due to the control mechanism used in the prototype, as the adjustments took at least 0.5 seconds. In such cases, the stopping and restarting of the feed takes one second.

3. System testing

The main test material was quenched and tempered steel 34CrNiMo6 not treated with Ca (hardness 320 HB). In most tests, the tool was manufactured by Sandvik (SNMM 120412-PR GC4015) and was equipped with a tool holder from the same manufacturer (DSBNL 2525M12, positioning angle 75°).

In addition, the tests used a rhomboidal tool by Sandvik (CNMM 120412-PR GC4015). The rhomboidal tool was held with a PCLNL 2525M12 holder (positioning angle 95°). Tests were carried out with pressure vessel steel P355NH as the cut material.

3.1. Turning tests for continuous chips

The aim of the turning tests was to research and develop the capacity of the system to detect problems based on signal data saved from sensors. Continuous chips occur with the material 34CrNiMo6 when the feed is low, typically 0.5 mm/r or lower, and when the cutting speed is 150-160 m/min. Continuous chips were not detected at high feeds. However, the test material was hard. With softer and more ductile materials, continuous chips are produced also at higher feeds. The depth of the cut varied in the tests between 1 and 4.5 mm.

3.1.1. Compiling a signal bank

First the features that allowed detecting a continuous chip had to be identified from the sensor signals. An experienced machinist made observations throughout the tests and recorded the observations in a test report. The criticality of the problem (continuous chip) was evaluated on a scale of 1-10. If there was no problem, the test report entry was 1. If a problem occurred at its worst, the report entry was 10. The machinist also entered into the report situations which would have required adjusting the cutting values. On the scale of 1-10, the lower values 1-5 indicated that the problem was not serious enough to require adjustments, whereas the higher values 6-10 indicated a need for adjustment. The observations of the machinist were then compared to the signals emitted by the system. Thus it was possible to isolate the features from the signals that allowed detecting continuous chips.

3.1.2. Detection tests of continuous chips

The detection tests of continuous chips aimed to create a cutting situation that generates a continuous chip. The arrangements were similar to the collection of the signal bank and enabled determining the detection rate. The detection rate was the percentage of situations defined by the machinist that the system could detect correctly, i.e. situations which the system and the machinist interpreted in the same way. The most difficult part of detecting continuous chips was establishing the detection threshold. The detection easily became either too sensitive or too rigid. In the latter case, the chip grew excessively long before it was identified. On the other hand, when the detection was too sensitive, the system categorized chips as too long even if they were tolerable for the process. When the appropriate detection threshold was established, the system correctly identified 76 out of 80. Therefore, the detection rate with the material 34CrNiMo6 and the tool Sandvik SNMM 120412-PR GC4015 was 95%, which is extremely high. The most common error in the detection was a false positive analysis, which meant that the system signalled a continuous chip even if there was none.

Detection tests were also carried out on pressure vessel steel P355NH, which was considerably softer and less ductile than the tested basic material (34CrNiMo6), due to which a higher cutting speed was used (300-500 m/min). In the tests, the identification with the material P355NH was less reliable than with the basic material. The typical problem that occurred was that the system claimed to detect a continuous chip when in fact there was none. False detections occurred especially at high cutting speeds (500 m/min). An analysis of the test results revealed a reason for the false identifications. The different characteristics of the material P355NH require a high cutting speed, due to which the detection of continuous chips should be carried out at a different frequency than for the material 34CrNiMo6. Changing the detection frequency area in the system does not require great efforts. Therefore, the detection of continuous chips could rather easily be adapted also to the material P355NH. Due to the small test sample, no detection rate was calculated for the material P355NH.

For the rhomboidal tool CNMM 120412-PR GC4015 and the tool holder PCLNL 2525M12, the tool angle is 95°, whereas for the tool SNMM 120412-PR GC4015 and the holder DSBNL 2525M12 the angle is 75°. In tests with the rhomboidal tool, the detection of continuous chips was flawless, and changing the positioning angle seemed to have no effect on it. However, the sample remained rather small, which means the effect of the tool angle requires further tests.

3.1.3. Adjustments to eliminate continuous chips

After the system was developed to a stage in which it detected continuous chips with sufficient reliability, the development of adjustment features was begun. In order to develop the adjustment features of the system, turning tests were conducted to study the reaction of the system to continuous chips. Based on these observations, the software part of the system was developed. Then, the improvements were tested to ensure their suitability for the system.

During machining, it is possible to adjust the feed (and cutting speed). The depth of the cut is entered into the system before the machining is started. Therefore, it remains constant during the machining within the limits set by the work piece and its form. Continuous chips can be eliminated by selecting the appropriate feed. Continuous chips occur if the feed is too low. The turning tests revealed that when continuous chips began to form, a mere increase in the feed was not enough to eliminate the problem, i.e. break the chip. Instead, increasing the feed without stopping if first often made the situation worse because the continuous chip only became thicker. Thus, the system was adjusted so that the system stopped the feed briefly (< 1 s) when continuous chips were formed. This broke off the chip. Then, the feed was restarted at a higher rate, which normally eliminates the problem. However, if the problem persists, the same course of action is repeated, and the feed is further increased. This greatly improved the reliability of the system, and if the chip detection works, the adjustment is also likely to work.

4. Conclusions

In the system created in this study, the detection rate of continuous chips was 95%. In conclusion, the system works very well with the combination of the tool and work piece material tested. Further studies need to establish how the detection algorithm of continuous chips should be adjusted when different cutting speeds and materials are applied.

The reaction time of the system from the detection of the problem to the adjustment of cutting values should be as short as possible. In the current system application, the long reaction time (5-10 seconds) may prove to be a problem in the turning of work pieces with a short cutting length. In such cases, the system has no time to make adjustments before the next chip, and no optimal cutting values can therefore be found. The feed and the cutting speed have an effect on how long a distance can be cut in a certain time span (reaction time). Especially rough turning would require a cutting length that allows time for adjustments. When the optimal values are determined, the distance in turning no longer has such a great impact. In terms of software and equipment, the reaction time can be reduced, which then relaxes the system requirements for the length of the chip. In the future, systems should be able to enter cutting values directly into the machine control. Thus one would not be as dependent on the original cutting speed, and one could freely choose how much one adjusts the cutting speed.

Wireless sensors would help to install the system on turning machines in production, in which case no inlets, tubes or mounting is required for cables. Acceleration sensors and acoustic emission sensors are attached to the tool holder. In manned production, changing the nose of the tool at certain intervals is easy, and sensors may only be needed in tool holders for rough turning tools. In unmanned production, however, roughing must be continued with a different tool when the nose is worn out. Therefore, also a different tool holder is applied because the tool cannot be rotated automatically. In consequence, unmanned production requires sensors in more than one tool holder.

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RUPIOJO TEKINIMO OPERACIJOS DROŽLIŲ VIJŲ SMULKINIMO IR ŠALINIMO KONTROLĖS SISTEMA

Reziumė

Straipsnyje pateikta prisitaikančioji rupiojo tekinimo operacijos drožlių kontrolės sistema. Drožlių vijos tipas nustatomas akustinės emisijos signalais detalės apdirbimo metu. Sistema valdo drožlių smulkinimą įvertindama jų ilgį ir šalina drožlių vijas stabdydama įrankio pastūmą, o paskui ją vėl įjungdama didesniu greičiu. Kontrolės mechanizmas grindžiamas programinės įrangos ir staklių valdymo įrenginio sąveika. Sistema testuota naudojant dviejų tipų pjovimo įrankius ir ruošinio medžiagą. Ateityje sukurtoji sistema bus tikrinama naudojant daugiau tipų įrankių ir medžiagų. Sistemai vis dar tobulintina greitinant reakciją ir paprastinant jutiklius. Sukurta drožlių vijų smulkinimo ir šalinimo sistema yra svarbus žingsnis automatiškai, nedalyvaujant žmonėms link.

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CHIP CONTROL SYSTEM FOR MONITORING THE BREAKING OF THE CHIPS AND ELIMINATION OF CONTINUOUS CHIPS IN ROUGH TURNING

Summary

This research project developed an adaptive chip control system for rough turning. Continuous chips are detected with the help of acoustic emission signals during machining. The system monitors the breaking of chips, estimates the length of the chips and eliminates continuous chips if those are formed by stopping the feed and then restarting it at a higher rate. The control mechanism is based on communication between the software and the lathe knob. The system was tested with two combinations of cutting tools and work piece material. In the future, the chip control system should also be tested with more tools and materials. The system still requires development, e.g. to shorten the reaction time and simplify the sensors. The chip control capacity of the system created in this study is an important step towards improving unmanned production.

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СИСТЕМА ДЛЯ КОНТРОЛЯ ИЗМЕЛЬЧЕНИЯ И УДАЛЕНИЯ ВИТКА СТРУЖКИ ПРИ ОПЕРАЦИИ ГРУБОГО ТОЧЕНИЯ

Резюме

В статье представлена научно исследовательская работа, предназначена для усовершенствования адаптивной системы контроля стружки при грубом точении. Тип витка стружки определяется во время обработки детали при помощи сигналов акустической эмиссии. Система управляет процессом измельчения стружек учитывая их длину, удаляет витки стружек путем уменьшения величины подачи инструмента, после чего ее увеличивает заново. Механизм контроля основан на взаимодействии программного обеспечения с системой управления станков. Для тестирования системы использовались инструменты и материалы заготовки двух типов. В будущем созданная система будет тестироваться при использовании более высокого количества инструментов и разных марок заготовок. Система требует усовершенствования, т.е. ускорения реакции и упрощения датчиков. Созданная система для измельчения и удаления витков стружек является важным шагом к автоматически управляемому производству без участия людей.

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