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(54) **Method of grinding**

(57) The present invention refers to a method of grinding, in which a continuous and combined variation of at least one rotation speed (Nw) of a ground work piece (P) and one approximation feed speed (Vf) between a grinding wheel (M) and the ground work piece (P) is performed throughout an entire grinding cycle.

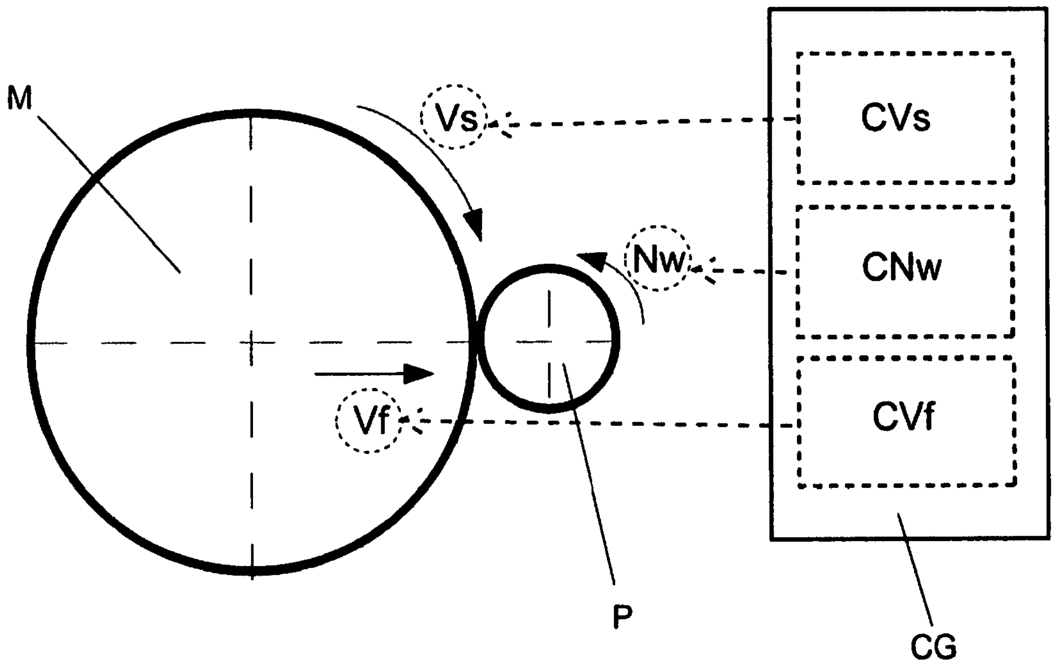

Fig. 4

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Description

Sector of the Art

[0001] The present invention relates to the methods of grinding carried out in grinding machines (flat grinding machines, centerless, cylindrical, universal, etc.), for the purpose of obtaining high precision machining both in dimensions and in surface finish.

State of the Art

[0002] Grinding is a manufacturing process widely used as a finishing technology. Cylindrical grinding or centerless grinding processes are among the most widely used grinding operations, the removal of material happens in these processes by a grinding cycle made up of multiple stages with constant feed ratios.

[0003] The grinding processes use a grinding wheel which machines a work piece during the grinding cycle, the process generally uses three main grinding speeds, a rotation speed of the ground work piece, a rotation speed of the grinding wheel and an approximation feed speed between the grinding wheel and the ground work piece.

[0004] There are many strategies for optimising the grinding cycle, all of them based on only varying the approximation feed speed between the grinding wheel and the ground work piece during the different stages forming a grinding cycle in a step-like and constant manner. In addition, the rotation speeds of the work piece and of the wheel do not undergo any type of variation and remain constant throughout the entire grinding cycle. The variation according to the constant steps causes abrupt jumps between stages of the feed speed which leads to the appearance of instabilities in the process, such as vibrations, causing an uneven finish on the surface of the work piece.

[0005] German patent application DE102006015038 discloses a method of centerless grinding in which the rotation speed of the work piece varies according to a sinusoidal function. This variation is used for preventing irregularities on the surface of the work piece caused by the appearance of vibrations. Although this solution partially minimises the appearance of vibrations it does not assure a correct surface finish of the ground work piece, since despite suggesting a variation of the rotation speed of the work piece according to a sinusoidal function and not keeping it constant as in the other conventional methods, it does not indicate that the approximation feed speed of the work piece is in an inconstant and step-like manner, and it also does not indicate that the rotation speed of the wheel is inconstant. Likewise, no combination of the grinding speeds is made in the solution of said German patent for obtaining a better surface finish of the work piece.

[0006] A method of grinding proposing a combination of the variation of the different speeds making up the grinding process is therefore necessary, such that the variation of said grinding speeds is produced according to the continuous functions throughout the entire time that the grinding cycle lasts.

Object of the invention

[0007] According to the present invention a method of grinding based on a continuous and combined variation of the speeds inherent to a grinding process which allows reducing the grinding cycle time, as well as eliminating undesired vibrations, maintaining the surface quality of the work piece in relation to roughness, roundness and diameter tolerance and the integrity of the work piece in relation to its hardness and tensional state is proposed.

[0008] The method of grinding object of the invention proposes varying at least the rotation speed of the ground work piece and the approximation feed speed between the grinding wheel and the ground work piece in a continuous and combined manner throughout the entire grinding cycle.

[0009] Additionally, in combination with the rotation speed of the ground work piece and the approximation feed speed between the grinding wheel and the ground work piece, the rotation speed of the grinding wheel is continuously varied. In the cases in which a regulating wheel is used to facilitate the grinding, the rotation speed of the regulating wheel is also varied in a continuous and combined manner.

[0010] It has been provided that signals in the form of ascending or descending ramps, sinusoidal, triangular or logarithmic signals, or any other type of signal assuring a progressive continuity throughout the entire time that the grinding cycle lasts are used for the continuous variation of the grinding speeds.

[0011] The method proposed by the invention improves the performance of the grinding process with respect to the conventional cycles, since the abrupt speed changes which can cause disturbances during the process are prevented. Furthermore, the application of this method considerably reduces the chatter and forced vibrations appearing both in the work piece and in the grinding wheel. The appearance of these vibrations during the grinding process leads to the generation of waves on the surfaces of the ground work piece and of the grinding wheel affecting the surface quality of the work piece (in terms of roundness, roughness or diameter tolerance) and the wear of the wheel, therefore the tolerances required are not achieved.

Description of the Drawings

[0012]

Figure 1 shows a diagram of a work piece and a grinding machine wheel with the different speeds that intervene during a grinding cycle.

Figure 2 shows the graphs with the feed speed of the wheel, the rotation speed of the wheel, and the rotation speed of the work piece according to a conventional grinding cycle.

Figure 3 shows the graphs with the feed speed of the wheel, the rotation speed of the wheel, and the rotation speed of the work piece according to a grinding cycle in accordance with the method of the invention.

Figure 4 shows a block diagram depicting the control which is performed on the different grinding speeds.

Figures 5a and 5b show the amplitude and frequency graphs in which the results obtained between the conventional method of grinding of Figure 2 and the method of grinding of the invention are compared.

Figures 6a to 6f depict different types of grinding to which the method of grinding of the invention can be applied.

Detailed Description of the invention

[0013] Figure 1 shows a diagram with the different speeds which can form part of a grinding process carried out in a conventional grinding machine. Thus, throughout the entire time of a grinding cycle (T) three speeds basically intervene between a grinding wheel (M) and a ground work piece (P), a rotation speed (Nw) of the ground work piece (P), a rotation speed (Vs) of the grinding wheel (M) and an approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P).

[0014] Figure 2 shows graphs in which a conventional grinding cycle is depicted. As can be observed, the conventional strategies apply constant grinding speeds which vary in a step-like manner during the grinding cycle (T). In the specific example of Figure 2, the approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P) varies in a constant and step-like manner during the different stages (t1, t2, t3, t4, t5) which the grinding cycle (T) lasts, whereas the rotation speed (Vs) of the grinding wheel (M) and the rotation speed (Nw) of the ground work piece (P) remain constant throughout the entire grinding cycle (T).

[0015] The step-like changes produce disturbances which affect the surface finish of the ground work piece (P), whereby the tolerances required are not achieved. One of the main drawbacks is the appearance of chatter and forced vibrations, appearing both in the ground work piece (P) and in the grinding wheel (M). The appearance of these vibrations during the grinding process leads to the generation of waves on the surfaces of the ground work piece (P) and of the grinding wheel (M) affecting the surface quality of the ground work piece (P) (in terms of roundness, roughness or diameter tolerance) and the wear of the grinding wheel (M).

[0016] For the purpose of improving the surface quality of the ground work piece (P) in relation to the roughness, roundness and diameter tolerance, as well as the integrity thereof in relation to its hardness, the invention proposes a method of grinding based on performing a continuous and combined variation of the different speeds forming part of the grinding process throughout the entire time that the grinding cycle (T) lasts. (See Figure 3).

[0017] According to an embodiment of the invention, at least the rotation speed (Nw) of the ground work piece (P) and the approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P) are varied in a continuous and combined manner, keeping for example the rotation speed (Vs) of the grinding wheel (M) constant. According to another embodiment of the invention, in combination with the rotation speed (Nw) of the ground work piece (P) and the approximation feed speed (Vf), the rotation speed (Vs) of the grinding wheel (M) is also continuously varied.

[0018] As can be observed in the block diagram of Figure 4, the variations of the grinding speeds (Vs, Vf, Nw) are continuously and independently controlled in respective control modules (CVs, CVf, CNw), and in an overall control module (CG) the favourable combination of said variations is performed according to the grinding strategy to be applied.

[0019] Once the variations of the grinding speeds are configured, the overall control module (CG) sends the orders of variation to each of the independent control modules (CVs, CVf, CNw) for controlling each of the grinding speeds, which modules execute the selected actions of variation. These control modules (CVs, CVf, CNw) act on the head of the grinding wheel (M), the head of the ground work piece (P) and on the carriage of the machine tool causing the feed approximation between the grinding wheel (M) and the ground work piece (P), thus varying the values thereof continuously depending on the established strategy.

[0020] The variations of the grinding speeds (Vs, Vf, Nw) can follow different types of signals depending on the objectives sought at the time of grinding the ground work piece (P), being able to be ascending or descending ramps, sinusoidal, triangular, logarithmic signals, etc., but always continuous signals throughout the entire grinding cycle. In the overall control module (CG) the start and end time of each of the variations of the grinding speeds (Vs, Vf, Nw), as well as the frequency and amplitude thereof are specified.

[0021] According to a non limiting example of the invention, the variation of the signal of rotation speed (Nw) of the ground work piece (P) is below 5 Hertz of frequency and its amplitude does not vary more than 50%. In the case of the grinding wheel (M), as it works at greater rotation speeds, the variation of the signal of rotation speed (Vs) is below 2 Hertz of frequency and its amplitude does not vary more than 50%. The variation of the signal of approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P) is below 5 Hertz of frequency and its amplitude can even reach 100%. The aforementioned amplitude values can vary depending on the grinding strategies used.

[0022] The strategies used for the variation of the grinding speeds are the function of two grinding parameters, the maximum chip thickness (h_{cu}) and the thermal damage of the work piece which is produced when a limit temperature (θ^*) is reached in the cutting area (contact area between the wheel and the work piece).

[0023] The maximum chip thickness (h_{cu}) influences the forces which are generated during the grinding, the surface finish of the ground work piece (P), the wear of the grinding wheel (M) or even the dynamic stability of the process. The grinding forces are the forces necessary for removing the material and are generated in the contact between the ground work piece (P) and the grinding wheel (M).

[0024] The relation between the grinding speeds (Vs, Vf, Nw) and the maximum chip thickness (h_{cu}) corresponds to the following equation:

$$h_{cu} = \left[\frac{4}{Cr} \left(\frac{v_w}{v_s} \right) \left(\frac{a}{d_e} \right)^{1/2} \right]^{1/2}$$

in which:

$C_r = C^*r$

"C" being the active density of the grains of the wheel and "r" is the shape factor of the grain (ratio between the width of the chip and the thickness of the chip);

d_e is the equivalent diameter of the process;

Vw is the peripheral speed of the ground work piece (P);

Vs is the rotation speed of the grinding wheel (M);

and "a" is the feed between wheel and work piece per each wheel rotation, which for the cylindrical grinding corresponds to the following expression:

$$a = \frac{v_f}{N_w}$$

"Vf" being the approximation feed speed between the grinding wheel (M) and the ground work piece (P); and "Nw" the rotation speed of the ground work piece (P).

[0025] By means of the continuous variation of the grinding speeds proposed by the invention, the time which the grinding cycle (T) lasts, the value which the maximum chip thickness (h_{cu}) has can be controlled, a matter which is not possible in conventional methods in which the speeds vary in a step-like manner during the different stages (tl, t2, t3, t4, t5) which the grinding cycle (T) lasts.

[0026] Thus, the greater the rotation speed (Nw) of the ground work piece (P), or the greater the approximation feed speed (Vf), the higher the maximum chip thickness (h_{cu}), while the greater the rotation speed (Vs) of the grinding wheel (M) the lower the maximum chip thickness (h_{cu}).

[0027] Better surface finishes are achieved for low chip thickness (h_{cu}) values by means of obtaining a lower roughness and roundness of the ground work piece (P), in addition to lower grinding forces.

[0028] The other grinding parameter which is taken into account for the variation of the grinding speeds is the thermal damage, which negatively affects the surface finish of the work piece. Thermal damage is produced when a limit temperature (θ^*) is reached in the cutting area defined between the grinding wheel (M) and the ground work piece (P). In general, the thermal damage is produced when the grinding power is higher than burnup power limit.

[0029] To prevent the appearance of thermal damage the invention proposes a favourable combination of grinding speeds. To that end, the combination of ideal grinding speeds during the first instances of the grinding cycle (T), where the approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P) acquires its highest value, is achieved for high rotation speeds (Nw) of the ground work piece (P) and for lower rotation speeds (Vs) of the grinding wheel (M).

[0030] An example of optimum speed combination for preventing the appearance of thermal damage in the ground work piece (P), while at the same time achieving a good surface finish is shown in the graph of Figure 3, where the grinding cycle (T) begins with a high approximation feed speed (Vf) and a high rotation speed (Nw), which are continuously reduced while at the same time the rotation speed (Vs) of the grinding wheel (M) increases from a low initial speed.

[0031] The vibration suppression or attenuation in the ground work piece (P) and in the grinding wheel (M) during the grinding is achieved by continuously varying the rotation speed (Nw) of the ground work piece (P) and the rotation speed (Vs) of the grinding wheel (M), whereby a disruption in the regeneration of the vibration is produced.

[0032] The vibrations can also be attenuated by minimising the grinding forces by means of a continuous reduction of the approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P). Thus, as seen in Figure 3, in the last section of the grinding cycle (T) the approximation feed speed (Vf) is progressively reduced to attenuate the vibrations.

[0033] Figures 5a and 5b show an experimental comparative of the vibrations which are produced for a constant and step-like approximation feed speed (Vf), such as that depicted in the conventional grinding cycle of Figure 2, and for a continuous and decreasing approximation feed speed (Vf), such as that depicted in the grinding cycle of Figure 3, according to the invention.

[0034] Figure 5a specifically shows the signal of vibration obtained with an accelerometer during the grinding process, reference (A) indicating the signal obtained for a continuous and decreasing speed and reference (B) the signal obtained for a constant and step-like speed. As can be observed, for the case of the invention at the end of the cycle the signal of vibration decreases (area referred to as section II).

[0035] A table with experimental results is shown below, in which it can be observed that for the case of the invention the values of roundness and roughness obtained are slightly lower with respect to the conventional case.

Cycle	Roughness Ra (μm)	Roundness (μm)
A	0.46	3.6
B	0.67	9.7

[0036] Next, experimental results are shown in which the improvements produced in a cylindrical grinding process upon applying the continuous variation of the rotation speed (Nw) and the continuous variation of the approximation feed speed (Vf) in a combined manner are observed, comparing the results obtained in this case with the results of an equivalent conventional cycle with constants and step-like speeds.

[0037] An improvement in the values of roughness and roundness for the grinding cycle with continuous speed variation proposed by the invention can be seen in the results obtained in relation to the surface quality of the ground work piece (P), the values of diameter tolerance of the ground work piece (P) being maintained. Furthermore, the table also shows the results obtained in both cases for a cycle with a spark out phase. Spark out is an end phase of the grinding, lasting around two seconds, which is based on making various passes until making the sparks disappear and improving the surface finish.

Cycle		Roughness (μm)	Roundness (μm)	Diameter tolerance (μm)
Conventional grinding constant speeds	with spark out	0.41	0.7	1
	without spark out	0.52	1.7	3
Grinding with continuous speed variation	with spark out	0.36	0.5	0
	without spark out	0.42	0.7	1

[0038] It is observed that the values obtained for the cycle with continuous speed variation without spark out are similar to the results obtained for the conventional cycle with spark out, whereby it is deduced that for required values of dimensional and surface tolerances the entire cycle time can be reduced applying the method of grinding of the invention, the two seconds of spark out time being eliminated in this example.

[0039] By way of illustrative example, Figures 6a to 6f show different grinding processes to which the method of grinding proposed by the invention can be applied, specifically an external plunge cylindrical grinding (Figure 6a), an internal plunge cylindrical grinding (Figure 6b), a flat grinding (Figure 6c), a centerless plunge grinding (Figure 6d), a centerless throughfeed grinding (Figure 6e) and a back and forth grinding. As these examples show, a regulating wheel (Mr) is used in certain grinding processes, being obvious for a person skilled in the art that the rotation speed (Nr) of the regulating wheel (Mr) can also be varied in a continuous and combined manner with the rest of the grinding speeds.

[0040] In addition, the method of continuous and combined variation of the grinding speeds can also be used for configuring the grinding processes known as grind-strengthening and grind-hardening.

[0041] The mechanical effects appearing during the last phases of finishing and spark out grinding cycles in grind-strengthening grinding produce an effect generating compression and hardening residual stresses of the surface layer of the ground work piece (P) due to the mechanically induced plastic deformation. This phenomenon leads to a greater wear resistance and fatigue resistance of the ground work pieces (P).By means of using the method of the continuous and combined variation of the grinding speeds it is also possible to control the amount of chip eliminated during the mentioned last phases of the grinding cycle, generating residual compression stresses and achieving an improvement in the surface quality of the ground work piece (P).

[0042] The grind-hardening grinding allows shortening the process times of machining work pieces replacing the heat treatment processes of conventional hardening. This grinding comprises obtaining a surface hardening of the ground work piece (P) and the finish thereof during the grinding operation itself. To that end, the heat generated in the contact area between the grinding wheel (M) and the ground work piece (P) is used for achieving the austenization thereof during the process. The greater current problem for the industrial application of this technology in cylindrical grinding resides in the appearance of the hardness slip phenomenon which describes a reduction of the depth of hardening in the overlapping area caused by the annealing effects or the decrease of the thermal load. The current techniques for preventing the hardness slip phenomenon are based on redesigning the initial geometry of the work piece. Obtaining a greater control of the depth of cut, heat generated, heat transmitted to the work piece and temperature reached at all times during the grinding process is possible by means of the method of the continuous and combined variation of the grinding speeds, whereby it forms a potential tool for assuring a constant thermal load on the circumference of the ground work piece (P).

Claims

1. A method of grinding using a grinding wheel (M) for machining a ground work piece (P) during a grinding cycle (T), at least three grinding speeds being used, which are a rotation speed (Nw) of the ground work piece (P), a rotation speed (Vs) of the grinding wheel (M) and an approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P), **characterised in that** a continuous and combined variation of at least the rotation speed (Nw) of the ground work piece (P) and the approximation feed speed (Vf) between the grinding wheel (M) and the ground work piece (P) is performed throughout the entire grinding cycle (T).

2. The method of grinding according to claim 1, **characterised in that** in combination with the rotation speed (Nw) of the ground work piece (P) and the approximation feed speed (Vf), the rotation speed (Vs) of the grinding wheel (M) is continuously varied.

3. The method of grinding according to claims 1 and 2, **characterised in that** in combination with the rotation speed (Nw) of the ground work piece (P), the approximation feed speed (Vf) and the rotation speed (Vs) of the grinding wheel (M), the rotation speed (Nr) of a regulating wheel (Mr) is continuously varied.

4. The method of grinding according to claim 1, **characterised in that** the grinding speeds vary continuously according to ascending or descending ramps, sinusoidal, triangular or logarithmic signals.

5. The method of grinding according to claim 1, **characterised in that** the grinding speeds are varied depending on the maximum chip thickness (h_{cu}) and on a limit temperature (θ^*) in the cutting area defined between the grinding wheel (M) and the ground work piece (P).

6. The method of grinding according to claims 1 and 2, **characterised in that** the approximation feed speed (Vf) and the rotation speed (Nw) of the grinding work piece decrease while the rotation speed (Vs) of the grinding wheel (M) increases.

7. The method of grinding according to the claims 1 and 2, **characterised in that** the variation of the rotation speed (Nw) of the ground work piece (P) is below 5 Hertz of frequency; the variation of the signal of rotation speed (Vs) of the grinding wheel (M) is below 2 Hertz of frequency and its amplitude does not vary more than 50%; and the variation of the signal of approximation feed speed (Vf) is below 5 Hertz.

8. The method of grinding according to claims 1 and 2, **characterised in that** the grinding speeds are continuously and independently controlled in respective control modules (CVs, CVf, CNw) and are combined in an overall control

module (CG).

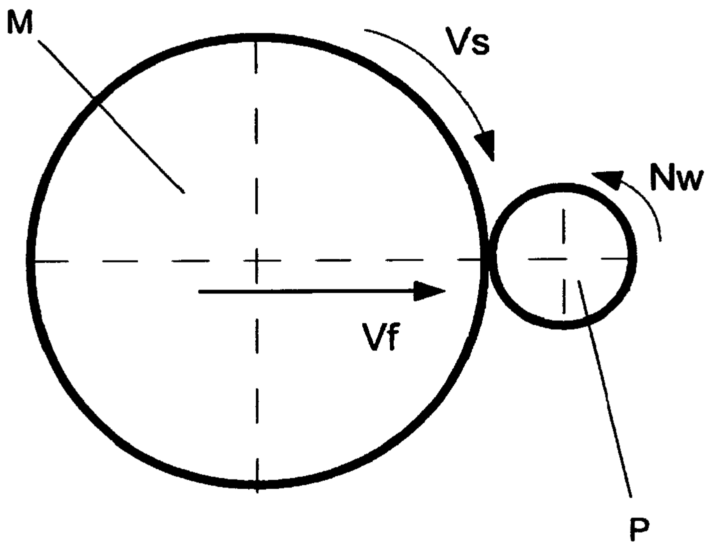

Fig. 1

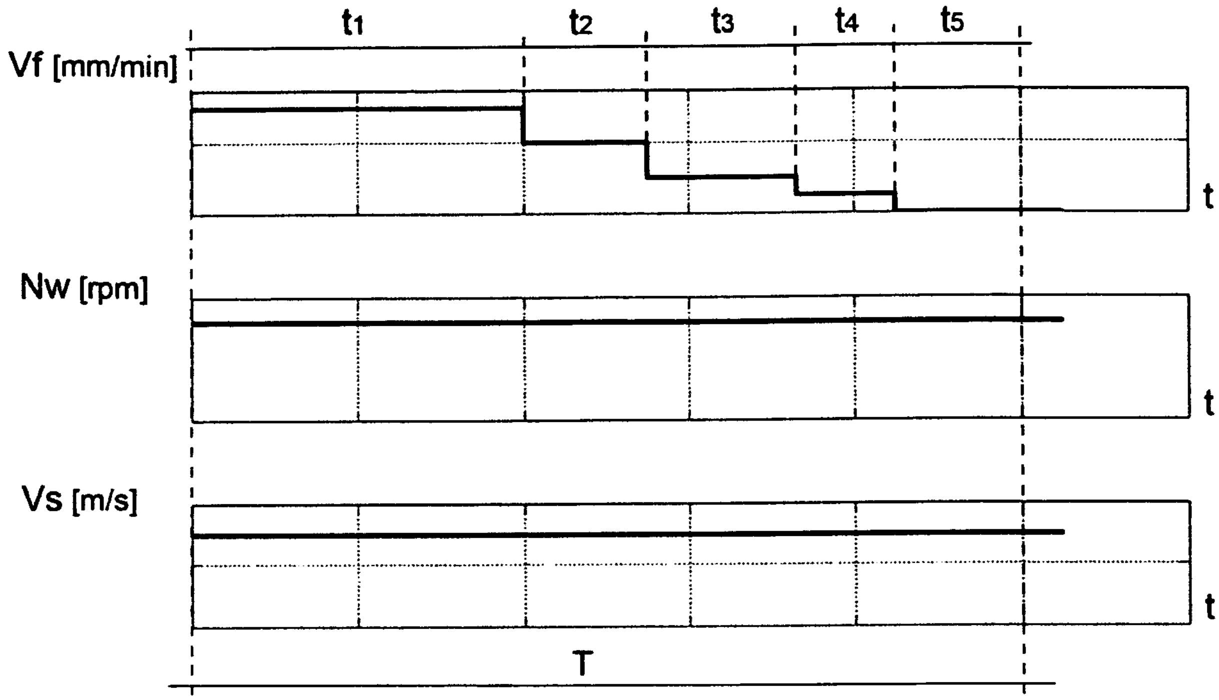
t1
t2
t3
t4
t5
Vf [mm/min]
t
Nw [rpm]
t
Vs [m/s]
t
T

Fig. 2

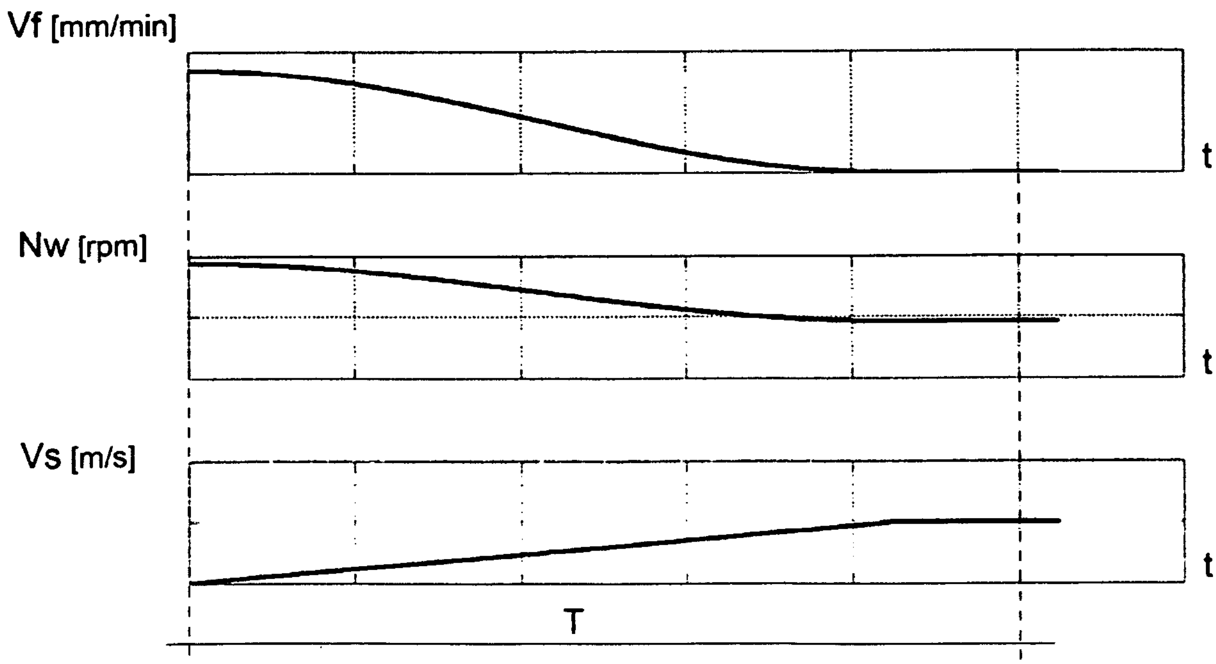
Vf [mm/min]
t
Nw [rpm]
t
Vs [m/s]
t
T

Fig. 3

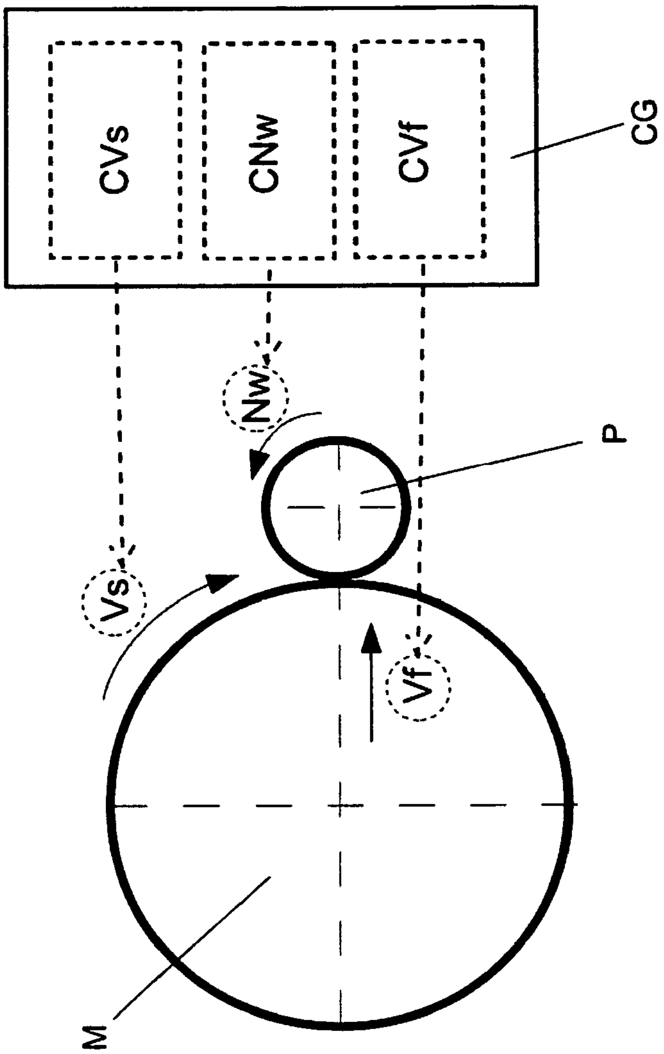

Fig. 4

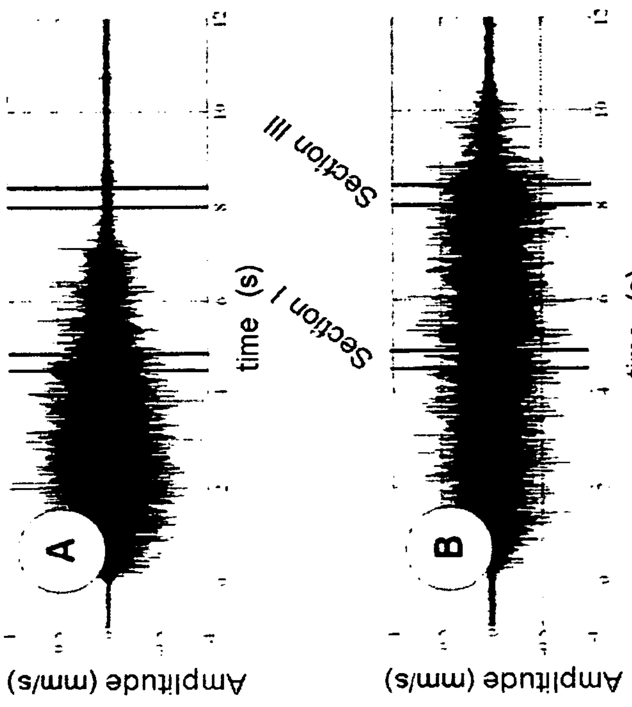
A
B
Section I
Section II
Section I
Section III
Amplitude (mm/s)
Amplitude (mm/s)
time (s)
time (s)

Fig. 5a

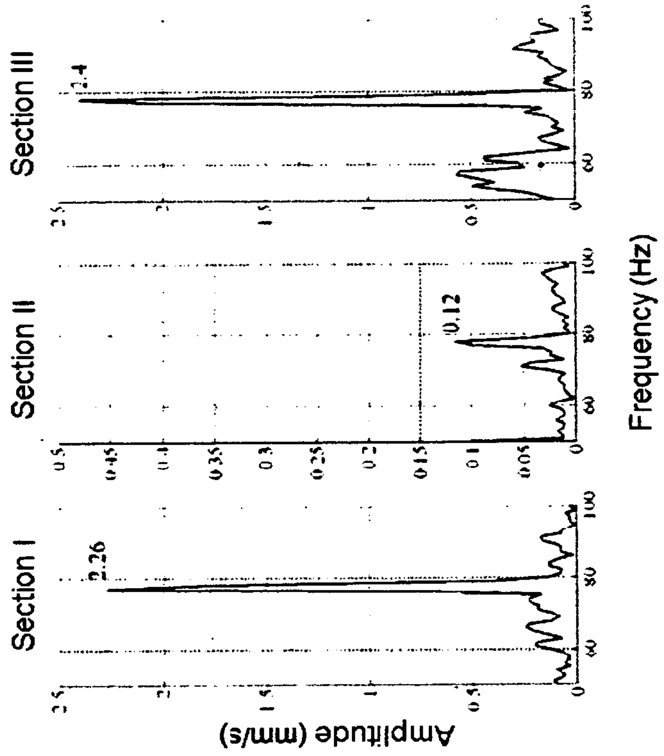
Section I
Section II
Section III
2.26
0.12
2.4
Amplitude (mm/s)
Frequency (Hz)

Fig. 5b

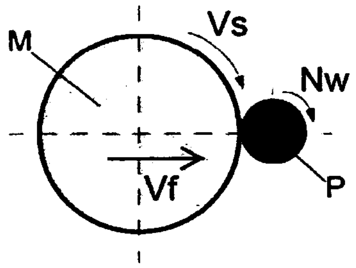

Fig. 6a

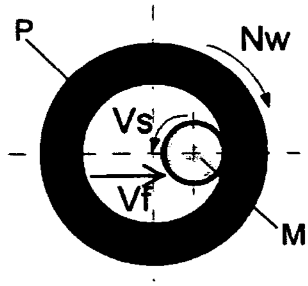

Fig. 6b

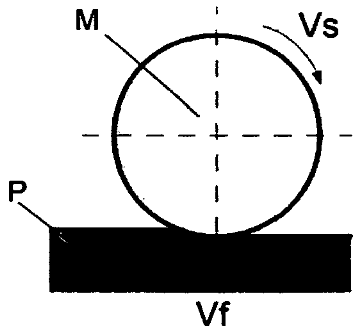

Fig. 6c

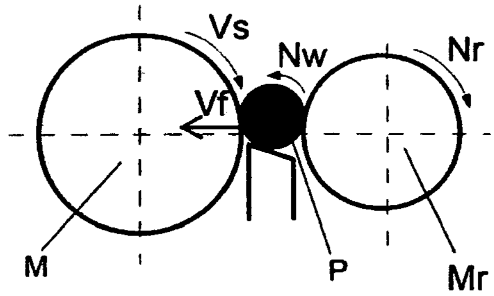

Fig. 6d

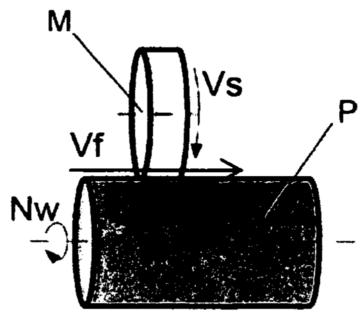

Fig. 6e

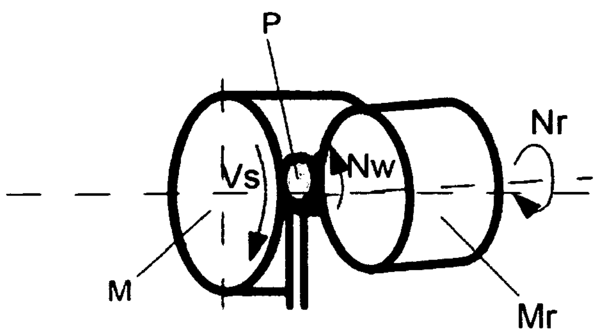

Fig. 6f

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EUROPEAN SEARCH REPORT

Application Number
EP 11 38 0106

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
Y,D	DE 10 2006 015038 A1 (SIEMENS AG [DE]) 11 October 2007 (2007-10-11) * the whole document * -----	1-8	INV. B24B1/00 B24B5/18
Y	US 2010/161107 A1 (KAPPMEYER GREGOR [DE] ET AL) 24 June 2010 (2010-06-24) * the whole document * -----	1-8	
A	DE 10 2010 023190 A1 (LIEBHERR VERZAHNTECH GMBH [DE]) 15 December 2011 (2011-12-15) * the whole document * -----	1-8	
A	DE 22 59 618 A1 (WERKZEUGMASCH OKT VEB) 26 July 1973 (1973-07-26) * the whole document * -----	1-8	

TECHNICAL FIELDS SEARCHED (IPC)

B24B
B23Q

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	6 June 2012	Watson, Stephanie

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EPO FORM 1503 03.82 (P04C01)

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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