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(54) **METHOD FOR MACHINING A WORKPIECE**

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(57) **ABSTRACT**

The invention relates to a method for machining a workpiece (**20**) on a numerically controlled machining device (**9**), whereby two or more machining steps (**11**, **12**, **13**) are provided for machining the workpiece (**20**). A machining data record (**28**) for controlling and/or adjusting the numerically controlled machining device (**9**) can be run in a control and/or adjustment device (**26**) of the numerically controlled machining device (**9**) together with a program (**30**) for operating the control and/or adjustment device (**26**). The machining data record (**28**) is used together with the program (**30**) for operating the control and/or adjustment device (**26**) to generate simulation data (**47**) in a simulation step. Subsequently, simulated material removal data (**49**) are generated from the simulation data (**47**) by means of a material removal simulation. The invention provides a simple method of controlling the machining steps of workpieces that are produced in a plurality of machining steps.

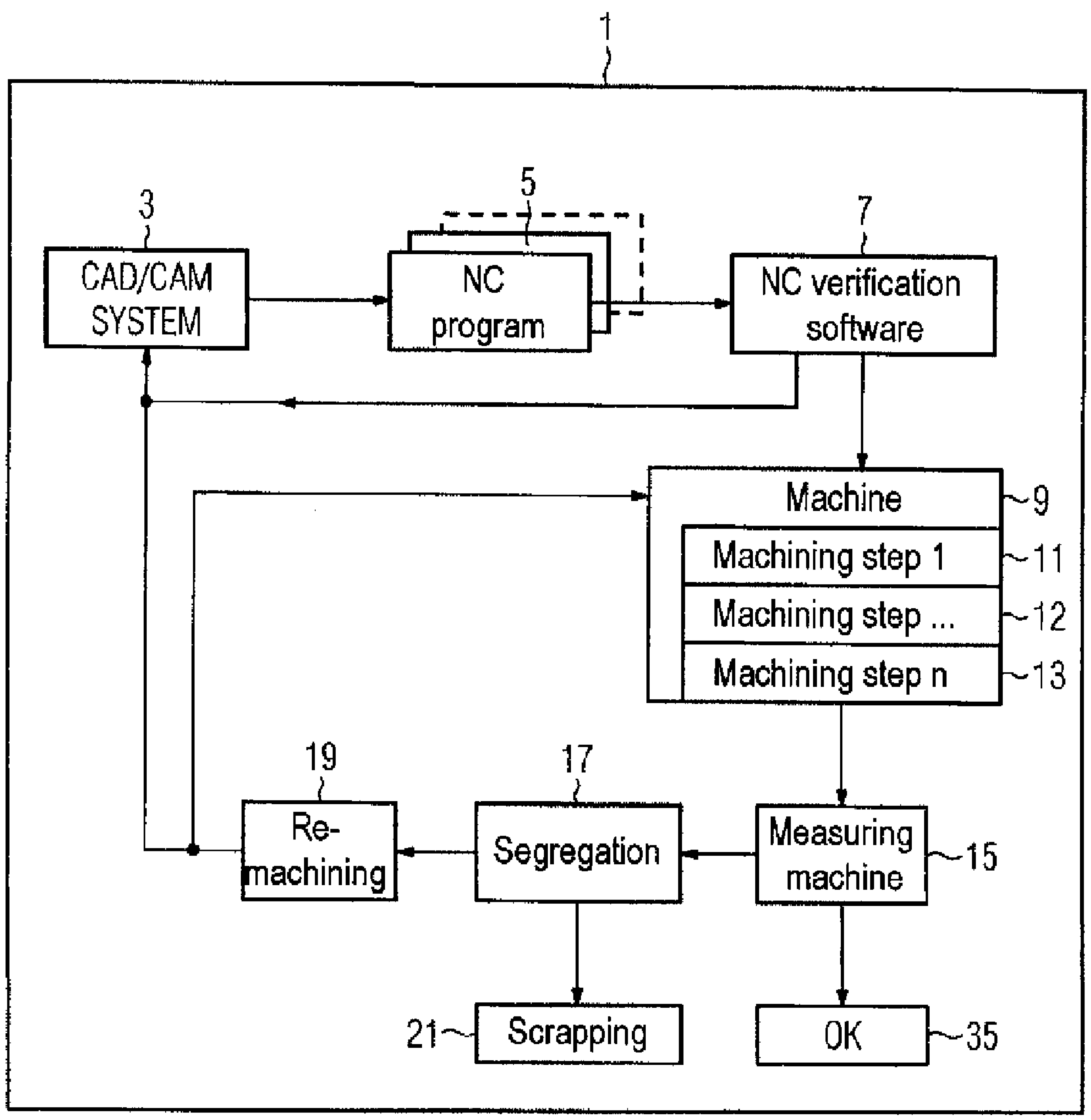


FIG 1

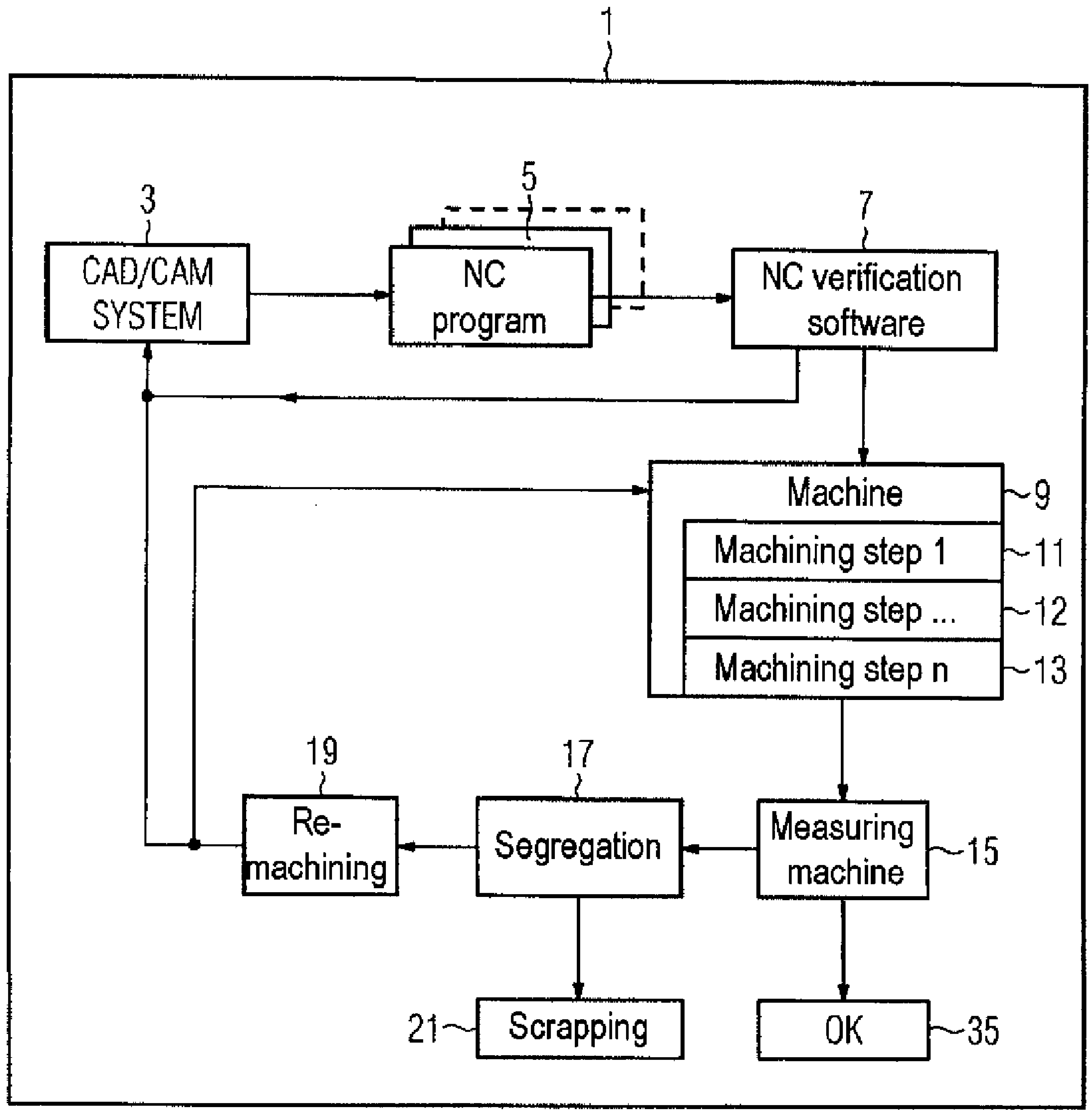
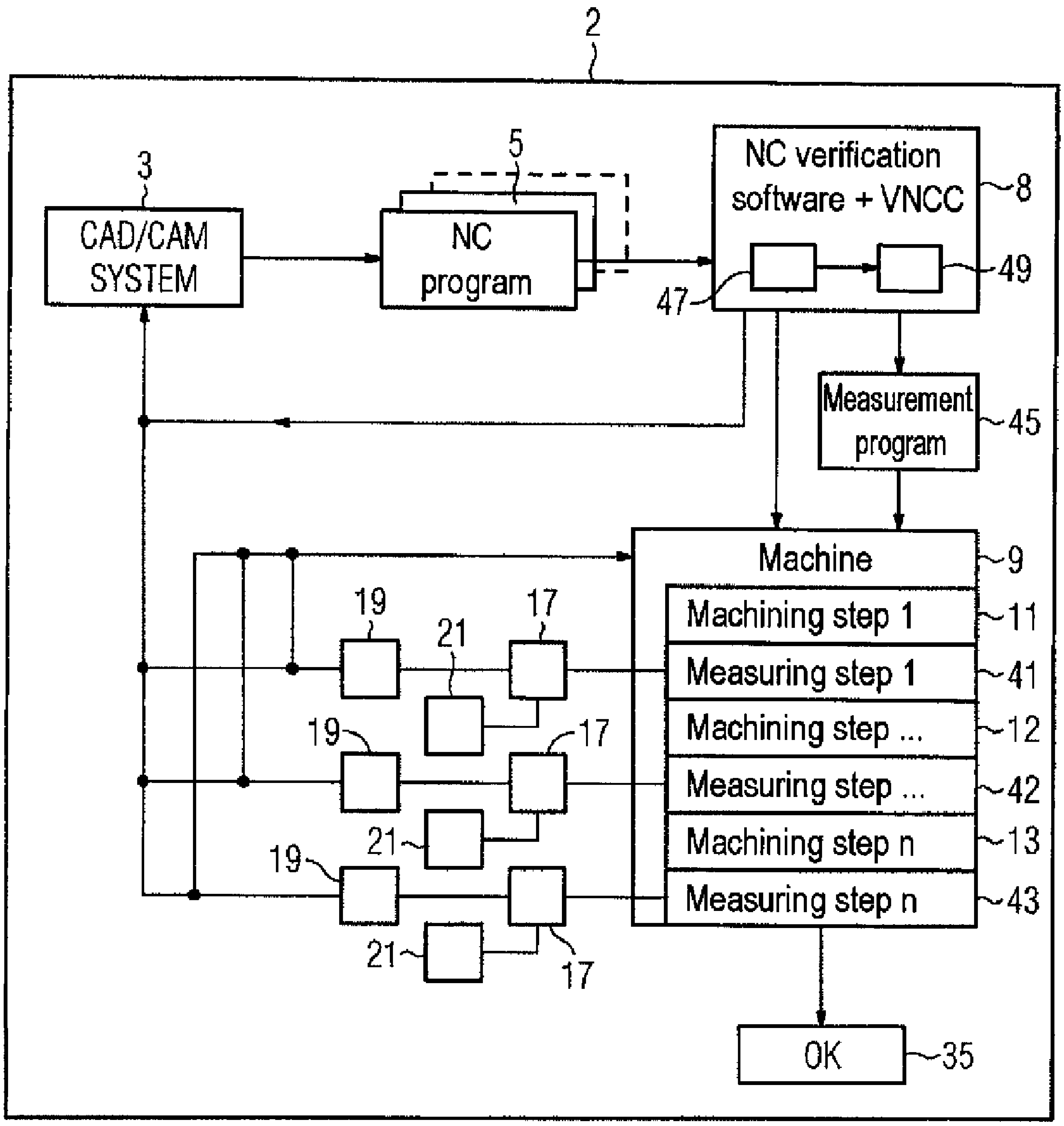
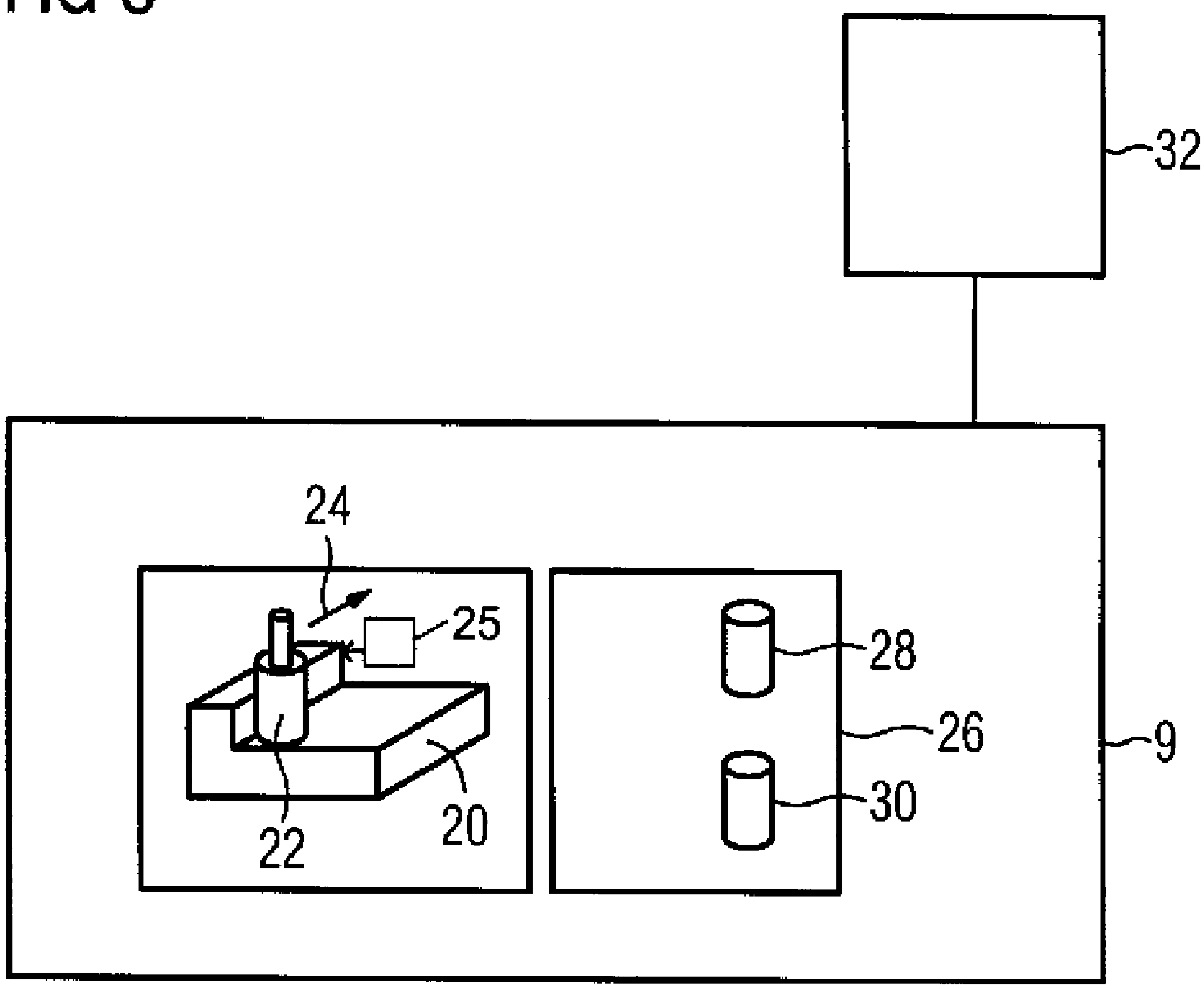

1
3
CAD/CAM SYSTEM
5
NC program
7
NC verification software
Machine
9
Machining step 1
11
Machining step ...
12
Machining step n
13
19
Re-machining
17
Segregation
Measuring machine
15
21
Scrapping
OK
35

FIG 2



2
3
CAD/CAM SYSTEM
5
NC program
NC verification software + VNCC
8
47
49
Measurement program
45
Machine
9
Machining step 1
11
Measuring step 1
41
Machining step ...
12
Measuring step ...
42
Machining step n
13
Measuring step n
43
19
21
17
OK
35

FIG 3



METHOD FOR MACHINING A WORKPIECE

[0001] The present invention relates to a method for machining a workpiece on a numerically controlled machining device, two or more machining steps being provided for machining the workpiece. Such a method also includes a simulation method for three-dimensional machining by a CNC-controlled machining device, in particular a milling machine, and a descriptive data record required for this purpose.

[0002] In the case of CNC-controlled machining devices, a workpiece is either directly coded by a programmer or the workpiece is modeled using a CAD system and is then converted into an equivalent CNC part program. In this case, the CNC part program and the CAD model correspond to idealized machining instructions for the machining device. The CNC program is loaded into a CNC controller and the machining device is controlled in accordance with the CNC program. If the workpiece which has been manufactured in this manner is within the desired manufacturing tolerances of an ideal workpiece, no problems arise with this procedure. However, if the manufactured workpiece does not meet the requirements imposed on it, the question arises as to which variations can be used as a basis for manufacturing a satisfactory workpiece.

[0003] Although it is possible to change individual machining instructions and/or individual operating parameters of the machining device in succession, to manufacture a new workpiece and then to check this newly manufactured workpiece in order to correct faults, this procedure is very laborious and is also intensive in terms of costs, materials and time. This is also very particularly true because it is often not known where to look for the cause of the discrepancies between the actually manufactured workpiece and the desired workpiece.

[0004] When manufacturing, in particular, complex parts, in particular parts with a high volume of removed material, as occur, for example, in aircraft construction or else in turbine construction for power plants, a plurality of process steps with different tools are necessary. Since there is no CAD model for the individual subprocesses for producing a part, the part being a workpiece, the quality of the subprocesses cannot be directly measured at present. Only the result of the overall process can be measured on a measuring machine or else on the manufacturing machine. This means that even faults which occurred as early as in the first process step can only ever be discovered after the entire part, for example a turbine blade, has been completed. This procedure may result in the following problems, for example:

- **[0005]** parts/workpieces are always finished even when irreparable damage to the part, which was not detected, occurred as early as shortly after the beginning of manufacture. Valuable machine time is thus wasted;
- **[0006]** the previously customary practice of measuring the parts on a measuring machine is very cost-intensive since, on the one hand, the measuring machines for large parts are very expensive and, on the other hand, the chucking of the workpieces, which are sometimes very large, onto the measuring machine is extremely complicated;
- **[0007]** production faults are often only detected weeks after the parts have been manufactured, with the result that a whole series of parts has been incorrectly manufactured in this time under certain circumstances;
- **[0008]** faults which have been detected in the previously known manner can be uniquely associated with a subprocess in the rarest cases, with the result that fault correction is again very complicated because all subprocesses have to be examined.

[0009] The object of the present invention is to provide a possible way of detecting faults during stepwise machining of a workpiece in a considerably faster, simpler and/or more cost-effective manner than in the prior art.

[0010] The object is achieved by means of a method for machining a workpiece that has the features as claimed in claim **1**. Dependent claims **2** to **9** develop further inventive methods for machining workpieces. Claim **10** relates to a system for carrying out one of the inventive methods.

[0011] In the inventive method for machining a workpiece on a numerically controlled machining device, two or more machining steps are needed to machine the workpiece and are accordingly also provided. A machining data record, which can be executed in a control and/or regulating device of the numerically controlled machining device together with a program for operating the control and/or regulating device, is provided for the purpose of controlling and/or regulating the numerically controlled machining device. The machining data record is, for example, at least one part program. The machining device is, in particular, a machine tool or else a production machine or an automatic handling machine. A machine tool may be provided, for example, for the following machining operations: drilling, milling, grinding, turning etc. The machining device has a control and/or regulating device, for example an NC controller or else a CNC controller, such controllers either being integrated in the machining device or else being functionally assigned to it. An operating system which is also referred to as an NC core (NCC) is needed to operate the control and/or regulating device. This NC core represents runtime software. Simulation data are generated according to the inventive method. These simulation data are generated in a simulation step from the machining data record together with the program (NCC) for operating the control and/or regulating device. The simulation can be carried out in one or else more steps. The simulation data are, in particular, the data which are produced as a result of the part program being processed by the NCC. In order to calculate these simulation data, it is possible to use either the real NC core on the control and/or regulating device or else a simulated NC core. The simulated NC core may also be referred to as a virtual NC core (VNCC), the latter running, for example, on a computer which is not provided for controlling and/or regulating the machining device. In a further developed embodiment, the VNCC is integrated in the control and/or regulating device. Furthermore, according to the inventive method, the simulation data are passed to a material removal simulation after they have been generated, simulated material removal data being generated from the simulation data. The geometry data of the workpiece can then be calculated from the simulated material removal data following a particular and/or any desired machining step by means of a calculation involving the original geometry data of the workpiece and just the material removal data. The geometry data following an x-th machining step are then advantageously compared with actually measured geometry data following the x-th machining step. If the measured geometry data correspond to the calculated—simulated—geometry data, the next machining step can be carried out. If the measured geometry data do not correspond to the calculated—simulated—geometry data, the discrepancy of the geometry data can be calculated. The discrepancy can be used as a basis for determining, in an automated manner, whether the workpiece to be machined can be used further by means of remachining or whether the workpiece to be machined must be withdrawn from further machining. In an advantageous manner, a machining record is either modified for a subsequent machining step, or else the machining record is recalculated for a machining step that is to be newly inserted, in an automated manner with the aid of the differing geometry data.

[0012] A simulation of an operation of machining a workpiece is used in the inventive method. In this case, the data record which describes the machining operation on the machining device—the machining data record—is used. Consequently, a desired machining operation by means of idealized machining instructions for the machining device can be determined on the basis of a descriptive initial data record. The initial data record is the description data record in this case.

[0013] The inventive method can be used to overcome fundamental disadvantages of the previously known method for machining a workpiece in a plurality of machining steps on a numerically controlled machining device.

[0014] NC verification software has previously been used for simulation but said software simulated the program for operating the machining device only to an insufficient extent. The software of the NC core itself is now used according to the invention to generate the simulation data. In this case, however, a virtual NC core (VNCC), that is to say an NC core which does not run on the machining device itself, can also be used. Since the VNCC reproduces the control behavior exactly, even minor geometric discrepancies which are generated by control functions, for example a compressor, rounding of corners or tool correction, can be detected as early as during simulation. As a result of the fact that such control functions which are present in the NC core are concomitantly taken into account when generating the simulation data, the accuracy of the latter is considerably increased. These data and the subsequent material removal simulation can be used to calculate the geometry data of intermediate steps in the operation of machining a workpiece in a very accurate manner. Accurate control of the precision of machining progress is thus always ensured since measured data can be compared with simulation data.

[0015] It is consequently advantageous if data are taken from the machining data record and/or from the program for operating the control and/or regulating device, the NC core, in the material removal simulation. For the rest, the use of the material removal simulation is also important because the NC core (NCC) or the VNCC has already concomitantly taken into account tool geometries, for example, in its initial data. Since different tools with different tool geometries can be used to manufacture the same workpieces using only one machining data record, that is to say only one part program for example, the NCC or the VNCC calculates different initial data on the basis of the tool geometry known to it. These possible variations can be corrected again using the material removal simulation. Simulated geometry data of a workpiece which can be used for intermediate measurements in order to verify that an operation of machining a workpiece is taking place correctly can consequently be generated from material removal data. Tool-specific data, for example radii of milling tools, are advantageously automatically transferred from the NCC or the VNCC to the material removal simulation.

[0016] In one advantageous refinement, the material removal simulation is used to generate a measurement program for each substep. It was previously the case that only the CAD model was available as a reference for measurement. That is to say only the completely machined part could ever be measured correctly. NC verification software with an attributed VNCC is now able to exactly represent the material removal for each machining step. It is thus able to generate a desired geometry after each step, said desired geometry corresponding to a CAD model for each process step. It is thus possible to reference the result of each substep to a geometry model and to generate the predefined desired values for control measurements after each step. These predefined desired values are in the form of measurement programs, for example, which are loaded onto the machine controller. The corresponding measurement program then exists for each machining program or program section.

[0017] The inventive method now makes it possible to directly check the result of each individual machining step on the machining device by introducing a measuring probe instead of the tool and executing a measurement program, for example. A machine operator can directly identify whether the result of the machining operation is in the permitted tolerance range by comparing the desired and actual values which can both be logged. In the event of a fault, the process is immediately interrupted and fault analysis can be started.

[0018] This procedure is considerably simpler than the conventional method since the fault can be associated with a single machining step. It also avoids valuable machine time being wasted with a part which has already been destroyed. If the result of each substep is positive, the measurement records provide the proof that the overall process was successful and the part produced corresponds to the specifications. There is thus no need for a separate measurement on a measuring machine. If the quality of the simulation and of the measurement is intended to be checked in the machining device using a measuring probe, it is additionally possible to use a measuring machine.

[0019] In order to improve the stability of the process of checking machining steps using simulation data, the machining device is periodically calibrated. This is ensured, for example, by means of a method which is used to monitor the state of the machining device and thus also its geometric quality at regular intervals of time. This is also known under the phrase "Electronic fingerprints for machine tools and production machines".

[0020] In another advantageous refinement, the NC core is integrated in a material removal simulation. This considerably improves, for example, the NC programs as early as at the programming station. Integration also affords the advantage that a reference geometry which makes it possible to automatically measure the partial results on the machining device is generated for each subprocess.

[0021] As a result of the inventive method, problems when machining a workpiece can be detected at the earliest possible time. It is possible to avoid the manufacturing process being continued and thus expensive machine time being wasted if incorrect material removal has taken place. The method highly simplifies fault analysis since faults can be directly associated with a subprocess. Causes of faults are detected more rapidly and can thus also be eliminated more rapidly. The expensive infrastructure for separately measuring the finished parts which is required according to the prior art can be dispensed with as a result of the inventive method without resulting in losses of quality.

[0022] In the case of an inventive method, it is possible to machine a workpiece in a first machining step in accordance with a first machining data record and to measure geometry data of the workpiece, after which the measured geometry data of the workpiece are compared with the simulated geometry data. If the geometry data do not correspond or if the predefined tolerances have been exceeded, a new machining data record which can be used to further machine the workpiece in corrected form in a subsequent machining step can be generated early on.

[0023] Geometry data can be compared, for example, as follows. A workpiece is machined in a first machining step in accordance with a first machining data record, after which geometry data of the workpiece are measured. Material removal data are then calculated from the measured geometry data of the workpiece, after which the calculated material removal data are compared with the simulated material removal data. In another advantageous refinement, the simulation is carried out in real time in parallel with the actual machining of the workpiece or else after the workpiece has been machined in a machining step since it is thus also possible to use data from the real NC core for the virtual NC core. Examples of such data are, in particular, fluctuating variables such as room temperature, fault messages etc.

[0024] In one advantageous refinement, as already commented above, the difference between the measured geometry data and the simulated geometry data or between the measured material removal data and the simulated material removal data is calculated, after which a machining data record which is provided for a subsequent machining step is modified depending on whether a difference threshold is exceeded.

[0025] The simulation of the NC core that is carried out in the invention can be carried out, for example, on the control and/or regulating device and/or on a simulation computer.

[0026] In addition to the method, the invention also relates to a corresponding system for carrying out the method. The system is designed in such a manner that, in addition to a means for simulating the program for operating a control and/or regulating device, it also has a means for simulating material removal. Furthermore, it advantageously also has a means for measuring the workpiece to be machined.

[0027] Examples of further advantages and details emerge from the following description of an exemplary embodiment. In this case:

[0028] FIG. **1** shows a basic illustration of a method for machining a workpiece in accordance with the previously known prior art,

[0029] FIG. **2** shows a basic illustration of an inventive method, and

[0030] FIG. **3** shows a basic illustration of a machining device in diagrammatic form.

[0031] The integrated system **1** which is illustrated in FIG. **1** and is intended to manufacture complex parts is known according to the prior art. The complex parts, that is to say parts/workpieces which need to be machined in a plurality of steps **11**, **12**, **13**, are modeled in a CAD (Computer Aided Design) system **3**. A CAM (Computer Aided Manufacturing) system could also be used, for example, instead of or else in addition to the CAD system **3**. The CAD system **3** generates, together with a post-processor, the part programs **5** needed to machine a workpiece. The part program **5** is an NC program. One single NC program and/or a plurality of NC programs **5** with a plurality of tool changes may be generated for the overall process of machining a workpiece, for example. However, it is also possible to generate a separate NC program for each tool. Machining with a tool corresponds to a subprocess. The NC programs **5** are then tested using a verification system **7**. The verification system **7** has NC verifications software, for example. Vericut® is one example of such verification software. During verification, collisions between chucking of the workpiece, for example in a machine tool, and the workpiece are checked, in particular. At the same time, a material removal simulation is used to check whether the NC programs result in the desired workpiece geometry. That is to say the result of the material removal simulation is compared with the original CAD model. If correspondence is within the fixed fault tolerances, the programs are released for manufacture and are transmitted to the machine controller of a machine, in particular a machining device **9**. The workpiece is manufactured using the NC programs **5**, which may last several hours to days, particularly in the case of parts (workpieces) having a high degree of material removal, for example approximately 95%. High degrees of material removal exhibit material removal of more than 80%, in particular. The machining device **9** carries out various steps **11**, **12** and **13** in the operation of machining the workpiece or workpieces. By way of example, only three machining steps **11**, **12** and **13** are shown in the illustration according to FIG. **1** but further steps are indicated in step **12**. The finished workpiece is then measured in a measuring step **15** on a measuring machine and is either certified **35** or segregated **37**. This operation may again last several days to weeks. If the workpiece is segregated **17**, it may either be remachined **19** in a remachining device (if too little material has been removed) or must be definitively scrapped **21**. In both cases of scrapping **21** and remachining **19**, however, production must be stopped and the source of the fault must be determined with laborious manual work. The practice of finding the source of the fault is used to reduce the segregation rate.

[0032] Possible types of faults which advantageously have to be or can be identified are listed below:

[0033] a faulty geometry of the parts

[0034] a machine fault

[0035] incorrect dimensions of a blank

[0036] dynamic problems during machining (for example: running-on faults)

[0037] faulty chucking of the part/workpiece

[0038] tool problems

[0039] temperature influences during machining

[0040] deformation of the part/workpiece during the machining process (bending, curvature)

[0041] The previously known method for machining a workpiece in a plurality of steps may entail at least one of the disadvantages specified below:

[0042] a fault is detected only after complete machining; if a problem occurs as early as in the first substep, work is nevertheless continued until the fault is detected; machine time is lost in this case;

[0043] production is continued until the fault has been detected; this may mean that a large number of additional faulty parts are produced, which entails a corresponding loss of time and material;

[0044] the operation of measuring the parts on the measuring machine **15** requires a complicated and costly infrastructure;

[0045] it is very difficult to associate a problem with a subprocess or a specific source of faults;

[0046] NC verification systems **7** according to the prior art have the disadvantage that the control behavior is emulated; this inevitably results in situations in which the material removal simulation corresponds only approximately to reality and geometric faults in the part program therefore cannot always be detected.

[0047] The illustration according to FIG. **2** shows, by way of example, an inventive method for machining a workpiece on a machining device. The machining device may be in the form, for example, of a milling machine or else another machine tool, for example a drilling machine or turning machine. The machining device could also be in the form of an industrial robot or a special machine.

[0048] In contrast to FIG. **1**, FIG. **2** illustrates NC verification software comprising a virtual NC core VNCC. This results in a verification system **8** which has been extended by the VNCC. In this case, the emulation software for a CNC system has been replaced with the VNCC. This enables an integrated system **2** which is improved in comparison with FIG. **1**. Since the VNCC reproduces the control behavior exactly, even minor geometric discrepancies which are generated by control functions, such as a compressor, rounding of corners or tool corrections, can be detected as early as during simulation. Furthermore, the extended verification system **8** has a material removal simulation. The material removal simulation is used to generate a measurement program for each substep **11**, **12** or **13** of a machining operation. It was previously the case that only the CAD model was available as a reference for measurement. That is to say only the completely machined part could ever be measured correctly. The extended NC verification software with the attributed VNCC is now able to exactly represent the material removal for each machining step **11**, **12** and **13**. It is thus possible to generate a desired geometry after each step, said desired geometry corresponding to a CAD model for each process step. It is thus possible to reference the result of each substep to a geometry model and to generate the predefined desired values for control measurements after each step. These predefined desired values are in the form of measurement programs **45** which can be loaded onto a machine controller. The corresponding measurement program **45** then exists for each machining program or program section. This makes it possible to directly check the result of each individual machining step **11**, **12** and **13** on the machine **9** by, for example, introducing a measuring probe and executing the measurement program **45**. A machine operator can directly identify whether the result of the machining operation is in the permitted tolerance range by comparing the desired and actual values which are both logged. In the event of a fault, the process is immediately interrupted and segregation **17** is carried out. Segregation **17** can be followed by scrapping **21** or remachining **19** depending on the severity of the fault. For remachining **19**, which is advantageously carried out on the machining device **9** again, a CAD/CAM system, for example, is used to generate at least one remachining NC program. If segregation **17** is required, fault analysis may be started. This fault analysis may result in one or more NC programs **5** being modified. This procedure is considerably simpler than the conventional method since the fault can be associated with a single machining step. It also avoids valuable machine time being wasted with a part which has already been destroyed. If the result of each substep is positive, the measurement records provide the proof that the overall process was successful and the part produced corresponds to the specifications. In order to improve the stability of the machining process, it is possible to periodically calibrate the machining device. This is ensured by means of a method which is used to monitor the state of the machine and thus also its geometric quality at regular intervals of time (Electronic fingerprints for machine tools and production machines).

[0049] The integrated system **2** according to FIG. **2** thus shows both a verification system **8** which has been extended by a VNCC and additional measurement programs **45** for measuring steps **41**, **42** and **43**. These additional measuring steps **41**, **42** and **43** make it possible to check each machining step **11**, **12** and **13**. However, it is not compulsory for each machining step to also be followed by a measuring step. The number of measuring steps **41**, **42** and **43** can be advantageously freely selected.

[0050] The illustration according to FIG. **3** shows a machining device **9** in diagrammatic form. The machining device **9** has a control and/or regulating device **26**. This control and/or regulating device **26** is provided for processing machining data records **28**. A program **30** is provided for the processing operation. This program is an NC core which is used as a type of operating system for the control and/or regulating device **26**. The machining data record **28** is provided for the purpose of describing the operation of machining a workpiece **20** with a tool **22**. The illustration according to FIG. **3** also shows a simulation computer **32** which can be used, for example, to simulate the NC core. This then corresponds to a virtual NC core (VNCC).

1.-**10**. (canceled)

11. A method for machining a workpiece on a numerically controlled processing machine in two or more machining steps, the method comprising the steps of:

executing in a control device of the processing machine a machining data record for machining the workpiece together with a program for controlling the numerically controlled processing machine,

generating, in a simulation step, simulation data from the machining data record in conjunction with the program that controls the numerically controlled processing machine, and

generating, in a material removal simulation step, from the simulation data simulated material removal data.

12. The method of claim **11**, wherein data from the machining data record or from the program that operates the control device, or both, are used in the material removal simulation.

13. The method of claim **11**, further comprising the step of generating simulated geometry data of the workpiece from the material removal data.

14. The method of claim **13**, further comprising the steps of machining a workpiece in a first machining step in accordance with a first machining data record, and comparing the measured geometry data of the workpiece with the simulation data.

15. The method of claim **11**, further comprising the steps of machining a workpiece in a first machining step in accordance with a first machining data record, measuring geometry data of the workpiece, calculating from the measured geometry data of the workpiece material removal data, and comparing the calculated material removal data with the simulated material removal data.

16. The method of claim **14**, further comprising the steps of calculating for a current machining step a difference between the measured geometry data and the simulated geometry data or between the measured material removal data and the simulated material removal data, and modifying a machining data record of a subsequent machining step depending on whether the difference exceeds a threshold value.

17. The method of claim **15**, further comprising the steps of calculating for a current machining step a difference between the measured geometry data and the simulated geometry data or between the measured material removal data and the simulated material removal data, and modifying a machining data record of a subsequent machining step depending on whether the difference exceeds a threshold value.

18. The method of claim **11**, wherein the machining data record is created using a CAD/CAM system.

19. The method of claim **11**, wherein simulated data or measured data or calculated data, or a combination thereof, are transferred to a CAD/CAM system.

20. The method of claim **11**, wherein the simulation step or the material removal simulation step, or both, are carried out on the control device or on a simulation computer.

21. A system for machining a workpiece on a numerically controlled processing machine, comprising

a control device configured to execute a machining data record for machining the workpiece together with a program for controlling the numerically controlled processing machine, to generate simulation data from the machining data record in conjunction with the program that controls the numerically controlled processing machine, and to generate from the simulation data simulating material removal data; and

a measuring probe for measuring the machined workpiece.

* * * * *