

CONTROLLING A MOVABLE ELEMENT IN A MACHINE TOOL

The present invention relates generally to machine tools such as milling, cutting, boring and grinding machines as well as traveling-wire or wire-cutting EDM (electrical discharge machining) machines, sinking-type EDM machines and other electroerosion or electrical machining equipments. More particularly, the invention relates to a method of and apparatus for controlledly moving a movable element such as a tool, tool electrode or workpiece, or tool holder, worktable or carriage supporting a tool or workpiece.

In a machine tool, a drive member such as a lead-screw arrangement is commonly coupled drivingly with a movable element and driven by motor means such as a DC motor or stepping motor energized by a feed signal to achieve a given movement of the movable element. In a numerical-controlled (NC) machine tool, the feed signal is a stream of pulses based upon digital commands preprogrammed on a record medium so that the desired movement may be performed as accurately as possible in accordance with the programmed commands. Such drive systems, however, commonly entail conversion of electrical to mechanical signals and further conversion of rotary mechanical to longitudinal mechanical signals or displacements. Thus, a mechanical error unavoidably develops in the stage of conversion due, for example, to an error in the lead or pitch of a lead screw and a backlash in various components. As a result, a precision electrical command is not accurately reproduced in a desired movement of the movable element. These errors are inherent in each particular machine tool and cannot generally be compensated for by a process of preprogramming with the conventional systems.

The present invention seeks to provide an improved method of and apparatus for controlledly moving a movable element in a machine tool, which method and apparatus overcome the aforementioned
5 problems encountered in the prior art.

Furthermore, the invention seeks to provide a method of and apparatus for controlledly moving a movable element in a machine tool whereby an extremely high precision of the displacement of the movable
10 member is assured.

In accordance with a first aspect of the present invention, there is provided a method of controlledly moving a movable element in a machine tool having a drive member drivingly coupled to the
15 movable element, motor means drivingly coupled to the drive member, and motor driver circuit means for energizing the motor means to drive the drive member, thereby to move the movable element, said method comprising the steps of:

20 (a) applying a sequence of feed signals from a command source to said motor driver circuit means, thereby energizing said motor means to achieve a corresponding sequence of desired movements of said movable element;

25 (b) sensing the actual displacement of said movable element resulting from the application of each of said feed signals to said driver circuit means and said motor means to provide a first signal as a function of said actual displacement;

30 (c) sensing said feed signals to provide a sequence of second signals each as a function of each of said feed signals;

(d) successively memorizing on a memory medium, said first signals corresponding to the

sequence of said second signals;

(e) successively reproducing said first signals memorized on said memory medium corresponding to the sequence of said second signals while
5 permitting said feed signals to be issued in sequence from said command source; and

(f) processing said reproduced first signals and said feed signals to provide a sequence of revised feed signals and applying said revised
10 feed signals to said motor driver circuit means, thereby to achieve the desired movements in sequence of said movable element.

In accordance with a second aspect of the invention there is provided an apparatus for
15 controlledly moving a movable element in a machine tool, comprising:

a drive member drivingly coupled to said movable element;

motor means drivingly coupled to said drive member;

motor driver circuit means for energizing said motor means to drive said drive member, thereby to move said movable element;

a command source for applying a sequence of feed signals to said motor driver circuit means, thereby to energize said motor means to achieve a corresponding sequence of desired movements of said movable element;

first sensing means directly responsive to the actual displacement of said movable element resulting from the application of each of said feed signals to said driver circuit means and said motor means for providing a first signal as a function of said actual displacement;

second sensing means responsive to said feed signals for providing a sequence of second signals each as a function of each of said feed signals;

memory means for successively memorizing said first signals corresponding to a sequence of said second signals;

readout means for said memory means to successively reproduce said first signals corresponding to a sequence of said second signals; and

logic means for processing said reproduced first signals and said feed signals to provide a sequence of revised feed signals and sequentially applying said revised feed signals to said driver circuit means and said motor means, thereby to achieve the desired sequence of movements of said movable element.

Machine Tool Apparatus and a method of

controlling the apparatus both embodying the invention will now be described by way of example, with reference to the accompanying diagrammatic drawings in which:

5 Fig. 1 is a schematic view, partly in section and partly in block form, diagrammatically illustrating an apparatus embodying the present invention;

10 Fig. 2 is a schematic diagram essentially in a block form illustrating, inter alia, a memory control unit constituting a portion of the embodiment of Fig. 1; and

15 Fig. 3 is a schematic diagram essentially in a block form illustrating, inter alia, a logic circuit unit constituting a portion of the embodiment of Fig. 1.

Referring to Fig. 1 the principles of the present invention are shown embodied in a traveling-wire or wire-cutting EDM machine. The machine includes a continuous wire electrode 1 which may be composed of copper or a copper alloy such as brass, and may have a thickness or diameter of 0.05 to 0.5 mm. The wire electrode 1 is fed continuously from a supply reel 2 shown mounted on a column 3 of
25 the machine and is collected onto

a take-up reel 4 shown mounted on an arm 5 extending from the column 3. Another arm 6 extends from the column 3 and has at its end a first wire-guide member 7. A second wire-guide member 8 is attached to a spindle 9 which is supported in a vertically displaceable manner by the upper arm 5. Thus, the wire electrode 1 is guided over the lower guide member 7 and the upper guide member 8 whose spacing is regulated by positioning the spindle 9 by means not shown, and is axially advanced between these members by drive means not shown but arranged in the path of wire travel on the side of the take-up reel 4 to give a suitable tension to the traveling wire electrode 1.

A workpiece 10 is disposed in a machining relationship with the wire electrode continuously traveling between the wire guide members 7 and 8. The workpiece 10 is fixedly mounted in a worktank 11 which is securely carried on a worktable assembly 12. A machining fluid, e.g. water, is supplied to the region of the workpiece 10 and the wire electrode 1 from one or more nozzles (not shown), while an EDM power supply (not shown) is connected electrically to the wire electrode 1 and the workpiece 10, to apply a succession of machining pulses across a fluid-filled machining gap formed between the traveling wire electrode 1 and the workpiece to remove material from the latter.

Shown at 13 is a feed or lead screw coupled to the table assembly 12 and rotated by a motor 14 to longitudinally move the table assembly 12 in the direction of a Y-axis. An encoder 15 is provided coupled rotatably with the rotary shaft of the motor 14 to sense an angular displacement thereof. Although not shown, an X-axis feed or lead screw is similarly coupled to the table assembly 12 and is

driven similarly by an X-axis motor (not shown) to move the assembly 12 longitudinally in the direction of an X-axis which extends perpendicular to the sheet of drawing. An encoder is similarly provided coupled rotatably with the rotary shaft of the X-axis motor to sense an angular displacement thereof.

A drive or feed signal to each of the X-axis and Y-axis motors is supplied along a line 16X, 16Y, from a numerical controller (NC) 16 which is here provided with a control memory circuit unit 17 and a control logic circuit unit 18, each of which is to be described hereinafter. The control memory circuit 17 includes a memory unit which may be constituted by a ROM (read-only memory), a RAM (random-access memory) and/or a magnetic tape conveniently held in a cassette for ease of entry and removal. The control logic circuit unit 18 may conveniently be constituted by a computer or central processing unit (e.g. microcomputer or microprocessor) to permit the unit 16 to perform computerized numerical control (CNC) functions.

Shown at 19 is a laser generator designed to emit a laser beam to the workpiece 10 to sense a displacement of the workpiece 10 with a high degree of precision. A prism 20 is disposed fixedly on the workpiece 10 surface, and a mirror 21 is disposed in the path of the laser beam to direct the laser beam reflected by the workpiece 10 surface to an optoelectrical converter 22 whose output electrical signals are applied to the control memory circuit unit 17. A reference scale along the Y-axis and a reference scale along the X-axis are shown at 23 and 24 respectively.

Further, thermometers 25, 26 and 27 are disposed in the regions of various critical machine

components. Thus, the thermometer 25 may be used to sense the temperature at a support for the machining guide 7, the thermometer 26 to sense the temperature at the workpiece 10 and the thermometer 27 to sense the temperature at a support for the machining guide 8. Each of the thermometers 25, 26 and 27 is adapted to convert the sensed temperature signal to a corresponding electrical signal. The electrical signals are applied to a computer 28 whose output signal is applied to the control memory circuit unit 17 via a lead 28b or alternatively may be applied directly to the control logic circuit unit 18 via a lead 28a.

A desired machining or contouring pattern to be imparted to the workpiece 10 during the operation of the wire-cutting EDM machine illustrated is given by a sequence of paths of movement of the worktable assembly 12 effected both along X- and Y-axes by the X-axis motor and Y-axis motor 14. The sequence of paths of movement is in turn dictated by the correspondingly prescribed instructions programmed in the NC unit 16. To effect each path of movement along each axis, the NC unit 16 furnishes a corresponding feed signal to each motor. This precise feed signal will not, however, be converted accurately into the corresponding or desired feed movement of the worktable assembly 12 or the workpiece 10 due to error factors inherently present in the drive system, for example, an error in the pitch or lead of the lead screw 13 and a backlash in the associated components. In accordance with the principles of the invention, an error in the displacement of the moved element 12 or workpiece 10 is sensed and controlledly memorized and processed to provide a revision in the feed signal applied to each

motor.

Referring to FIG. 2, the structure and operation of a certain embodiment of the control memory circuit unit 17 may be described. In this arrangement which relates to the Y-axis movement by way of example, the optoelectrical transducer 22 provides the control memory circuit unit 17 with an analog input which represents the position of the workpiece 10 sensed through the laser beam. The control memory circuit unit 17 comprises an analog-to-digital (AD) converter 121 which converts the analog position signal into a train of digital pulses which are counted by a counter 122, while the sensing output pulses of the encoder 15 are counted by a counter 124. A comparator 123 compares the count levels of the counters 122 and 124 and provides a difference in counts which is latched or temporarily stored in a latch counter 125. The sensing output pulses of the encoder 15 are also counted by counters 128 and 129 to cause a successive operation of a read-only-memory (ROM) 126. A timing pulse generator 127 is responsive to an output of the counter 128 to provide a timing pulse each time an increment of displacement is counted to enable the signal latched in the circuit 125 to be memorized in the ROM 126. Each instant a timing pulse is generated, both counters 122 and 124 are cleared and the differential count between the actual displacement of the workpiece 10 and the output of the encoder per each increment of displacement is transferred from the latch counter 125 to the ROM 126. Thus the differential values in the successive increments of displacement are successively accumulated and stored in the ROM 126. A switch 130 is used to clear the count of all the counters.

The actual displacement of the workpiece 11 is measured with an extremely high degree of accuracy by the laser arrangement 19, 20, 21 and 22. A differential value between such an actual
5 displacement of the moved member 10 measured and an encoder 14 output which represents a displacement of the motor 14 shaft effected in response to a feed signal is thus ascertained for each incremental feed, the values being successively memorized over
10 successive incremental feeds. The memorizing operation is performed prior to a given machining operation. Thus an error inherent in the lead screw 13 which gives rise to an error in the actual displacement of the moved member, the workpiece 10 or
15 the worktable assembly 12, is memorized in the ROM 126 in each of a sequence of incremental feeds directed by preprogrammed instructions of the NC unit 16. The memorized error in the ROM 126 is read out and the corrected feed signals are applied to the
20 motor 14.

FIG. 3 shows an embodiment of the control logic circuit unit 18. An explanation will again be given with reference to displacement along the Y-axis. A signal from the NC unit 16 is applied to a
25 waveform-shaping circuit 131 whose output is applied to a flip-flop 132 which thus provides digital signals. The latter signals are applied via a discriminator 133 to the up or down terminal of an up/down or reversible counter 134. Meanwhile a
30 preset counter 139 counts the sensing output pulses of the encoder 15 to provide an output signal which is applied to a read-out circuit 138 for the ROM 126. The memory in the latter is read out and applied to a waveform-shaping circuit 136. A flip-flop 137
35 converts the shaped signal to digital pulses which

are applied via the discriminator 133 to the up or down terminal of the counter 134. The counter 134 performs a count-up or count-down until a preset upper or lower limit is reached. Then an output
5 issues through a waveform-shaping circuit 135 and is applied to a differential control circuit 142 through a first input thereof and in turn to a driver circuit 143 to controlledly drive the motor 14. A waveform-shaping circuit 141 is interposed between the counter
10 139 and a second input of the differential control circuit 142. An oscillator 140 is used to operate the two flip-flop 132 and 137.

In operation, the motor 14 is driven to drive the lead screw 13 which in turn moves the
15 worktable assembly 12 and hence the workpiece 10. An angular displacement of the motor 14 or the lead screw 13 is sensed by the encoder 15, which thus produces pulses corresponding to the angular displacement effected in response to a feed signal
20 applied to the motor 14. The encoder 15 here may also provide a rate signal from the number of pulses per unit time in addition to the position or displacement signal corresponding to the pulse number. The encoder 15 output is accumulated in the
25 preset counter 139 and each time the sensed pulses reach a preset number the counter 139 issues a signal pulse to enable the readout circuit 138. The memory contents in the ROM 126 are thus successively read out and applied via the circuit 136 to the flip-flop
30 137 where they are converted into digital signals. The latter are then applied via the discriminator 133 to the counter 134 into which the preprogrammed feed signals are incoming from the NC unit 16. The counter 134 thus provides the feed signals revised by
35 the error-compensating signals from the memory

unit 126 through its differential counting operation. The revised feed signal from the counter 134 is reformed through the waveform-shaping circuit 135 and passes through the differential control circuit 142 and the driver circuit 143 to energize the motor 14, thereby precisely moving the worktable assembly 12 as commanded in spite of inherent error in the mechanical system connecting the motor 14 to the assembly 12.

10 The workpiece 10 is securely mounted on the worktable assembly 12 and is held in a predetermined machining position with the wire electrode 1. Accordingly a desired machining contour is achieved with an extremely high degree of precision. It should be apparent that a similar drive mechanism incorporating the error-compensation arrangement described hereinbefore may be used along one or more axes in an X-Z plane orthogonal to the Y-axis described.

20 It is apparent from the foregoing that in spite of presence of errors in pitch or lead of the feed screw 13 these errors are in effect ascertained by a high degree of precision measurement through the laser arrangement 19,20,21,22, and an error in each of the incremental feeds is successively memorized in the control memory unit 17 preparatory to a given machining operation. In the actual machining operation, the memorized error signals are reproduced synchronously with the sequence of preprogrammed feed signals being supplied from the NC or command source 16 so that a revised sequence of feed signals develop and are applied to the motor, thereby precisely moving the movable element as desired.

35 The use of an encoder as a detector for providing a reference signal responsive to a feed

signal is advantageous because this allows detecting the rate of displacement. Thus the output pulses of the counter 139 may be applied to the differential control circuit 142 and a rate-deviation signal which develops at the output of the differential control circuit 142 may be applied to the motor 14 to control the velocity or rate of angular displacement of its rotary shaft. In this manner a positioning control with an increased response sensitivity is achieved.

10 It has further been found that a thermal deformation (expansion) which various critical machine components suffer causes a serious machining positioning error. This error is effectively compensated for according to further features of the invention. Thus, as shown in FIG. 1, thermometers 15 25, 26 and 27 are disposed to sense the temperatures of the machining guide member 7 or its support arm 6, the workpiece 10 and the machining guide member 8 or its support member 9 to provide the corresponding 20 electrical signals. The thermal deformation (expansion) of each part is known from the temperature thereof as sensed and the corresponding electrical signals as developed at the output of the thermometer 25, 26 and 27. The judgment circuit or 25 computer 28 fed with the temperature signals then analyzes the influences of the thermal deformation (expansions) of the respective parts on the effective position of the workpiece 10 relative to the axis of the traveling wire tool 1, and provides a 30 compensation signal which can be applied via a line 28a directly to the logic circuit 18, thereby revising the feed signal applied to the motor 14. The circuit 28 may alternatively be a simple joining circuit and then the analysis may be conducted by the logic 35 circuit 18. The judging circuit or computer 28 may

also provide a sequence of signals representing the influence of the thermal expansion of the sensed components on the position of the workpiece known as a function of time. The sequence of such signals may
5 be applied via a line 28b to the memory unit 17 and the memorized signals may be reproduced and applied to the preprogrammed feed signals from the NC unit 16 in the course of machining operation. An increased machining accuracy is thus achieved irrespective of
10 thermal deformations (expansions) of those critical machine components.

It will be understood that the motor in the system may be either of rotary or linear type. An AC motor may be provided with a phase-controlled driver
15 circuit. A stepping motor and a DC motor should, of course, be fed by "pulsing" and "continuous" drive circuits, respectively, which are well known in the art. A fluid motor or electrofluidic motor may likewise be employed. Means for sensing the
20 operating displacement of the motor or the drive member (e.g. lead screw) is advantageously constituted by an encoder of rotary type as shown or of linear type, although any other detector of the similar function may alternatively be employed such
25 as an inductor tachometer, moire-fringe sensor, resolver or magnetic scale. The command source is advantageously an NC unit of conventional design but may be a copying system of known form. The means directly responsive to a displacement of the movable
30 member is not limited to the laser arrangement shown but, among others, may advantageously make use of an ultrasonic sensing system as described in European Patent Publication No. 0006022A1 published
12 December 1979.

35 There is thus provided an improved method

as well as apparatus for controlledly moving a
movable member in a machine tool whereby an extremely
high displacement accuracy is assured.

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CLAIMS

1. A method of controlledly moving a movable element in a machine tool having a drive member drivingly coupled to the movable element, motor means
5 drivingly coupled to the drive member, and motor driver circuit means for energizing the motor means to drive the drive member, thereby to move the movable element, said method comprising the steps of:
- (a) applying a sequence of feed signals
10 from a command source to said motor driver circuit means, thereby energizing said motor means to achieve a corresponding sequence of desired movements of said movable element;
- (b) sensing the actual displacement of said
15 movable element resulting from the application of each of said feed signals to said driver circuit means and said motor means to provide a first signal as a function of said actual displacement;
- (c) sensing said feed signals to provide a
20 sequence of second signals each as a function of each of said feed signals;
- (d) successively memorizing on a memory medium, said first signals corresponding to the sequence of said second signals;
- 25 (e) successively reproducing said first signals memorized on said memory medium corresponding to the sequence of said second signals while permitting said feed signals to be issued in sequence from said command source; and
- 30 (f) processing said reproduced first signals and said feed signals to provide a sequence of revised feed signals and applying said revised feed signals to said motor driver circuit means, thereby to achieve the desired movements in sequence of said
35 movable element.



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2. The method defined in Claim 1 wherein step (b) comprises producing said first signal as a deviation of said actual displacement of the movable element from a desired displacement thereof dictated by said feed signal.
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3. The method defined in Claim 1 wherein in step (c) said second signal is produced by sensing an operating displacement of said motor means resulting from the application of each of said feed signals to said motor driver circuit means.
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4. The method defined in Claim 3 wherein step (b) comprises producing said first signal as a deviation of said actual displacement of the movable element from said operating displacement of the motor means.
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5. The method defined in Claim 1 wherein in step (c) said second signal is produced by sensing and operating displacement of said drive member resulting from the application of each of said feed signals to said motor driver circuit means.
20
6. The method defined in Claim 5 wherein in step (b) comprises producing said first signal as a deviation of said actual displacement of the movable element from said operating displacement of the drive member.
25
7. The method defined in any one of the Claims 1 to 6 wherein in step (d) said first signals are successively memorized on said memory medium corresponding directly to the sequence of said feed signals.
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8. The method defined in any one of the Claims 1 to 6 wherein in step (e) said first signals memorized on said memory medium are successively reproduced corresponding directly to the sequence of said feed signals.
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9. The method defined in Claim 7 wherein in step (e) said first signals memorized on said memory medium are successively reproduced corresponding directly to the sequence of said feed signals.

5 10. The method defined in any one of Claims 1 to 9 wherein in step (b) said actual displacement of the movable element is sensed by measuring the position of said movable element with a laser beam.

11. A method as defined in any preceding claims,
10 further comprising the steps of sensing a temperature of at least one critical machine component, converting the sensed temperature into a corresponding electrical signal representing a thermal deformation of said component, deriving from said electrical
15 signal a correction signal and combining said feed signals and said correction signal to compensate for an error in positioning said movable element due to the thermal deformation of said component.

12. The method defined in Claim 11 wherein said
20 at least one component comprises said movable element.

13. The method defined in Claim 11 or 12 wherein said electrical or correction signal is memorized in conjunction with step (d) and is reproduced in conjunction with step (e).
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14. An apparatus for controlledly moving a movable element in a machine tool, comprising:

a drive member drivingly coupled to said movable element;

5 motor means drivingly coupled to said drive member;

motor driver circuit means for energizing said motor means to drive said drive member, thereby to move said movable element;

10 a command source for applying a sequence of feed signals to said motor driver circuit means, thereby to energize said motor means to achieve a corresponding sequence of desired movements of said movable element;

15 first sensing means directly responsive to the actual displacement of said movable element resulting from the application of each of said feed signals to said driver circuit means and said motor means for providing a first signal as a function of said actual displacement;

20 second sensing means responsive to said feed signals for providing a sequence of second signals each as a function of each of said feed signals;

25 memory means for successively memorizing said first signals corresponding to a sequence of said second signals;

readout means for said memory means to successively reproduce said first signals
30 corresponding to a sequence of said second signals; and

logic means for processing said reproduced first signals and said feed signals to provide a sequence of revised feed signals and sequentially
35 applying said revised feed signals to said driver



circuit means and said motor means, thereby to achieve the desired sequence of movements of said movable element.

15. The apparatus defined in Claim 14 wherein
5 said first sensing means is arranged to provide said first signal as a deviation of said actual displacement of the movable element from a desired displacement thereof dictated by said feed signal.

16. The apparatus defined in Claim 14 or in
10 Claim 15 wherein said second sensing means is responsive to an operating displacement of the motor means resulting from the application of each of said feed signals to said driver circuit means.

17. The apparatus defined in Claim 16 wherein
15 said first sensing means is arranged to provide said first signal as a deviation of said displacement of the movable element from said operating displacement of the motor means.

18. The apparatus defined in Claim 14 wherein
20 said second sensing means is responsive to an operating displacement of said drive means resulting from the application of each of said feed signals to said driver circuit means.

19. The apparatus defined in Claim 18 wherein
25 said first sensing means is adapted to provide said first signal as a deviation of said actual displacement of the movable element from said operating displacement of the drive member.

20. The apparatus defined in any one of the
30 Claims 14 to 19 wherein said memory means is adapted to successively memorize said first signals corresponding directly to the sequence of said feed signals.

21. The apparatus defined in any one of the
35 Claims 14 to 20 wherein said readout means is adapted



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to successively reproduce said first signals corresponding directly to the sequence of said feed signals.

5 22. The apparatus defined in any one of the Claims 14 to 21 wherein said first sensing means comprises means for measuring the position of said movable element with a laser beam.

10 23. An apparatus as defined in any one of the Claims 14 to 22, further comprising measuring means for measuring a temperature of at least one critical machine component, means for converting the sensed temperature into a corresponding electrical signal representing a thermal deformation of said component, means for deriving from said electrical signal a
15 correction signal and means for combining said feed signals and a correction signal to compensate for an error in positioning said movable element due to the thermal deformation of said component.

20 24. The apparatus defined in Claim 23 wherein said at least one critical component includes said movable element.

25. The apparatus defined in Claim 24 wherein said movable element is a workpiece.

25 26. The apparatus defined in any one of the Claims 23 to 25 wherein said at least one critical component includes at least one member for supporting a tool for machining said workpiece.

30 27. An apparatus for controlledly moving a movable element in a machine tool, substantially as hereinbefore described with reference to, and as illustrated by, the accompanying drawings.

35 28. A method of controlledly moving a movable element in a machine tool, substantially as hereinbefore described with reference to, and as illustrated by, the accompanying drawings.

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29. A machine tool having a movable element and an apparatus according to any one of the Claims 14 to 28 for controlledly moving said movable element.

30. A workpiece machined on a machine tool
5 according to Claim 29, or by a machining method which incorporates a method according to any one of the Claims 1 to 13 and 28.

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