

POLISHING TOOL

FIELD

This invention relates to a polishing tool, and in particular, to a polishing tool having a continuous range of compliance.

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BACKGROUND

Abrasive polishing is an important manufacturing process in many industries ranging from ship-building to biomedical fields. In general, close dimensional precision is needed for aerospace, automotive, biomedical components like turbine blades, power-transmitting shafts, knee implants, and so on. It is therefore necessary to use a polishing tool with a correct compliance in order to produce desired material removal, thereby increasing dimensional accuracy and reducing rework which increases time and cost. During polishing, the material removal profile is highly influenced by the contact pressure between the polishing tool and workpiece. For a constant force and speed operating condition, the tool stiffness plays a crucial role in altering the contact area and maximum material removal depth. Presently in industries, according to the contour of the surface to be polished and the nature of the polishing operation such as rough or fine finishing, the compliance of the tool is considered. For example, a felt pad which is very compliant in nature, cannot be used for removing weld seams and a very stiff pad made of glass fibre cannot be used to polish intricate surfaces or blending two surfaces. Hence considerable space for storing these tools, and time is taken to change each time is an added problem.

Currently, many polishing tools are provided with different compliances in order to polish different workpieces having different polishing requirements. Such polishing tools typically comprise flexible abrasive discs provided on rubber backing pads having different rubber hardness, for example, such as “hard”, “medium” or “soft” as shown in FIG. 1, that is directly relatable to compliance of the tool, where a “hard” rubber backing pad is the stiffest and a “soft” rubber backing pad is the least stiff. Using a tool with a hard rubber backing pad, material removal by the abrasive disc during polishing is mostly concentrated in a region near a first point of contact between the abrasive disc and the workpiece, as can be seen in FIG. 2a, whereas using a tool with a soft rubber backing pad, material removal during polishing is more equally distributed, as can be seen in FIG. 2b. This is due to the effect of compliance of the rubber backing pad on the contact pressure between the abrasive disc and the workpiece. In order to polish intricate surfaces, a very soft pad that provides better flexibility could be used, but this takes more time to complete polishing of the entire workpiece. In another example, if a

weld component is to be polished, more pressure is required initially to polish the weld region, while a soft tool is required in later passes to blend the weld region with the normal surrounding surface. Choice of polishing tool is currently dependent on human operator experience and the selection process requires skill as well as time. Furthermore, while use of robots theoretically reduces time and cost, presently, robotic polishing typically maintains a constant force using force control in the robot, even for polishing complex components. However, constant force does not assure constant pressure and can lead to undesirable uneven material removal.

10 SUMMARY

Disclosed is a polishing tool having a continuous range of compliance that allows a single tool to work with changes in contour and desired amount of material to be removed from a workpiece or between different workpieces, and that may be readily adapted for use with robots. This provides better dimensional accuracy by controlling the material removal rate at intricate regions, and reduces tool changing time which is a major concern in mass production. The polishing tool has stiffeners that control the compliance of a rubber backing pad through movement of the stiffeners in and out of the rubber backing pad. The tool has a bearing assembly that can transmit both linear and rotary motion simultaneously, thereby allowing a stiffener carrier to move up and down along a main shaft of the tool while rotating or spinning the rubber backing pad. In this way, changes in tool compliance can be effected while machining or polishing continues without requiring stops to change tools or adjust tool compliance, so that the tool can be considered an active tool as opposed to a passive one. Using an active tool saves time and cost while the tool is adaptable to different shapes and suitable for polishing complex contours as a continuous compliance range is provided in place of discrete compliance found in traditional fixed-compliance rubber backing pads of different hardness.

According to a first aspect, there is provided a polishing tool comprising: a rubber pad provided with a number of channels; and a corresponding number of stiffeners receivable in the channels to slidably engage the channels; wherein an increase in length of the stiffeners in the channels increases stiffness and decreases compliance of the rubber pad.

The rubber pad may be provided at one end of a shaft configured to be attached to a spindle, wherein one end of each of the stiffeners is secured to a stiffener carrier provided about the shaft.

The stiffener carrier may be provided with a flange bushing, the flange bushing allowing linear movement of the stiffener carrier along the shaft, the flange bushing and stiffener carrier rotating together with the shaft when the shaft is rotated by the spindle.

- 5 The polishing tool may further comprise a bearing assembly, the bearing assembly comprising a bearing housing and a bearing provided about the shaft, the bearing provided between the bearing housing and the stiffener carrier to allow rotation of the stiffener carrier relative to the bearing housing.
- 10 The polishing tool may further comprise a protective tube provided around each stiffener within the channels.

The protective tube may be made of nylon.

- 15 The stiffeners may comprise steel wires.

According to a second aspect, there is provided polishing system comprising: the polishing tool of the first aspect; and a linear actuator to control position of the stiffeners within the channels.

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The polishing system may further comprise a connecting rod provided to transmit linear actuation from the linear actuator to the stiffener carrier.

- 25 According to a third aspect, there is provided a rubber pad for a polishing tool, the rubber pad comprising: a number of channels to slidably engage a corresponding number of stiffeners received therein, wherein an increase in length of the stiffeners in the channels increases stiffness and decreases compliance of the rubber pad.

- 30 For the first and third aspects, the channels may comprise hollow ribs provided on a rear surface of the rubber pad.

The hollow ribs may be integrally formed with the rubber pad.

- 35 The channels may have channel openings adjacent a geometric centre of the rubber pad, the stiffeners entering the channels at the channel openings.

The channels may radiate symmetrically from adjacent the geometric centre of the rubber pad.
The channels may extend to an outer edge of the polishing pad.

5 BRIEF DESCRIPTION OF FIGURES

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments of the present invention, the description being with reference to the accompanying illustrative drawings.

- 10 FIG. 1 (prior art) is an illustration of rubber backing pads of different hardness.
FIG. 2a (prior art) is a material removal profile under a 20N force with a relative hard rubber backing pad.
FIG. 2b (prior art) is a material removal profile under a 20N force with a relative soft rubber backing pad.
- 15 FIG. 3 is a front view of an exemplary embodiment of a polishing tool.
FIG. 4a is a three-dimensional cross-section model of portion of the polishing tool of FIG. 3 with stiffeners at a fully inserted position.
FIG. 4b is a three-dimensional cross-section model of a portion of the polishing tool of FIG. 3 with stiffeners at a retracted position.
- 20 FIG. 5 is a longitudinal section view of the polishing tool of FIG. 3.
FIG. 6 is a longitudinal section view of a bearing assembly of the polishing tool of FIG. 3.
FIG. 7 is a perspective view of an exemplary flange bushing of the bearing assembly of FIG. 6.
FIG. 8 is a perspective view of an exemplary ball bearing of the bearing assembly of FIG. 6.
FIG. 9 is a top perspective view of an exemplary rubber pad of the polishing tool of FIG. 3.
- 25 FIG. 10 is a top perspective view of an exemplary embodiment of a polishing system comprising the polishing tool of FIG. 3.
FIG. 11 is a photograph of a mould with plastic plugs used to form the rubber pad of FIG. 9.
FIG. 12a is a photograph of an assembly of a rubber pad, a shaft, protective tubes, stiffeners and a flange bushing.
- 30 FIG. 12b is a photograph of the assembly of FIG. 12a assembled with a stiffener carrier and a ball bearing.
FIG. 12c is a photograph of a complete assembly of the polishing tool including a bearing housing.
- FIG. 13a is a photograph of the stiffeners at an initial fully inserted position in the rubber pad.
- 35 FIG. 13b is a photograph of the stiffeners at 7.5mm retracted position.

- FIG. 13c is a photograph of the stiffeners at 15 mm retracted position.
- FIG. 14 is a photograph of a static pressure distribution test set-up of the tool on a universal testing machine in contact with a workpiece.
- FIG. 15a is a photograph of the test-setup of FIG. 14 with use of a pressure film.
- 5 FIG. 15b is a photograph of the pressure film showing developed colour after testing.
- FIG. 16 is a plot of load versus downward displacement response obtained at 15N force at three different stiffener positions.
- FIG. 17a is a MATLAB plot of pressure distribution obtained under a load of 10N with the stiffeners at an initial fully inserted position in the rubber pad.
- 10 FIG. 17b is MATLAB plot of pressure distribution obtained under a load of 10N with the stiffeners at 7.5mm retracted position.
- FIG. 17c is a MATLAB plot of pressure distribution obtained under a load of 10N with the stiffeners at 15 mm retracted position.
- FIG. 18a is a MATLAB plot of pressure distribution obtained under a load of 15N with the stiffeners at an initial fully inserted position in the rubber pad.
- 15 FIG. 18b is MATLAB plot of pressure distribution obtained under a load of 15N with the stiffeners at 7.5mm retracted position.
- FIG. 18c is a MATLAB plot of pressure distribution obtained under a load of 15N with the stiffeners at 15 mm retracted position.
- 20 FIG. 19 is a plot of contact area vs. stiffener retraction position.
- FIG. 20 is an image of a meshed tool assembly with boundary conditions.
- FIG. 21 is a plot of stress-strain curves for different hyperelastic models for tensile data.
- FIG. 22a is a cross-sectional view of the tool on a workpiece under a load of 15N with the stiffeners at an initial fully inserted position in the rubber pad.
- 25 FIG. 22b is cross-sectional view of the tool on a workpiece under a load of 15N with the stiffeners at 7.5mm retracted position.
- FIG. 22c is a cross-sectional view of the tool on a workpiece under a load of 15N with the stiffeners at 15 mm retracted position.
- FIG. 23a is a plot of experimental and simulated load versus downward displacement response obtained at 15N force with the stiffeners at an initial fully inserted position in the rubber pad.
- 30 FIG. 23b is plot of experimental and simulated load versus downward displacement response obtained at 15N force with the stiffeners at 7.5mm retracted position.
- FIG. 23c is a plot of experimental and simulated load versus downward displacement response obtained at 15N force with the stiffeners at 15 mm retracted position.
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FIG. 24a shows simulated contact pressure distribution with the stiffeners at an initial fully inserted position in the rubber pad.

FIG. 24b shows simulated contact pressure distribution with the stiffeners at 7.5mm retracted position.

5 FIG. 24c shows simulated contact pressure distribution with the stiffeners at 15 mm retracted position.

FIG. 25a is a photograph of a machining experimental set-up in a multi-process micro-machining system.

FIG. 25b is a photograph of a close-up of the tool in the experimental set-up of FIG. 25a.

10 FIG. 26a shows material removal profile obtained under a load of 10N with the stiffeners at an initial fully inserted position in the rubber pad.

FIG. 26b shows material removal profile obtained under a load of 10N with the stiffeners at 7.5mm retracted position.

15 FIG. 26c shows material removal profile obtained under a load of 10N with the stiffeners at 15 mm retracted position.

FIG. 27a shows material removal profile obtained under a load of 15N with the stiffeners at an initial fully inserted position in the rubber pad.

FIG. 27b shows material removal profile obtained under a load of 15N with the stiffeners at 7.5mm retracted position.

20 FIG. 27c shows material removal profile obtained under a load of 15N with the stiffeners at 15 mm retracted position.

FIG. 28 is a plot of stiffener retraction against maximum material removal depth under both 10N and 15N loads.

FIG. 29 is a plot of stiffener retraction against contact area under 15N load.

25 FIG. 30 is a photograph of a polishing system in an experimental polishing set-up with the polishing tool normal to the workpiece.

FIG. 31a is a photograph of polishing with stiffeners completely inserted in the rubber pad.

FIG. 31b is a photograph of polishing with stiffeners in a retracted position.

30 FIG. 32 is a plot of material removal depth against material removal width at different stiffener positions.

FIG. 33 is a photograph of a polishing system in a robotic polishing set-up.

FIG. 34a is a photograph of polishing a curved surface with stiffeners completely inserted in the rubber pad.

FIG. 34b is a photograph of polishing a curved surface with stiffeners in a retracted position.

35 FIG. 35 shows superimposed profiles of curved surfaces polished with the tool having

stiffeners in fully inserted and fully retracted positions.

DETAILED DESCRIPTION

Exemplary embodiments of a polishing tool 10 will be described below with reference to
5 FIGS. 3 to 35. The same reference numerals are used throughout the figures for the same or similar parts.

In general, as can be seen in FIGS. 3 to 5, the polishing tool 10 comprises a rubber pad 20 provided with channels 22 and stiffeners 30 that are receivable in the channels 22 to slidably
10 engage the channels 22, such that an increase in length of the stiffeners 30 in the channels 22 increases stiffness and decreases compliance of the rubber pad 20. The term 'rubber' throughout the specification is used to mean any appropriate elastic material and may comprise natural rubber or synthetic rubber including silicone rubber and the like. The channels 22 may be in the form of hollow ribs 22 provided on a rear surface 29 of the rubber pad 20, with the
15 stiffeners 30 being insertable and retractable within the hollow ribs 22. The channels 22 have channel openings 25 that are preferably adjacent a geometric centre of the rubber pad 20 and the stiffeners 30 enter the channels 22 at these channel openings 25. The channels 22 preferably extend to an outer edge of the rubber pad 20 to allow maximum stiffness of the rubber pad 20 to be achieved by full insertion of the stiffeners 30 so that the stiffeners 30
20 extend over the radius of the rubber pad 20. The stiffeners 30 may comprise steel wires. The hollow ribs 22 are preferably integral the rubber pad 20, and may be raised on the rear surface 29 of the rubber pad 20.

In use, an abrasive disc 26 may be provided on a front surface 21 of the rubber pad 20, and
25 pressure distribution on the workpiece 100 when the abrasive disc 90 is applied to the workpiece 100 by the tool 10 is expected to change in accordance with the position of the stiffeners 30 inside the hollow ribs 22. Relative position of the stiffeners 30 within the hollow ribs 22 thus determines compliance of the rubber pad 20.

30 As shown in FIG. 4a, when the stiffeners 30 are in a fully inserted position in the hollow ribs 22, the rubber pad 20 becomes relatively stiffer. As shown in FIG. 4b, when the stiffeners 30 are in a retracted position, the rubber pad 20 becomes relatively more compliant, so that when in the retracted position, the contact pressure of the tool with the workpiece 100 is expected to be less than that when in the fully inserted position, due to the increased compliance of the tool
35 resulting in greater contact area between the tool and the workpiece 100 while applied force

remains the same, leading to a lower material removal depth.

The tool 10 includes a rotatable shaft 40 at one end of which the rubber pad 20 is provided. The shaft 40 is configured to be attached to a spindle to rotate the tool 10 for polishing. The tool 10 further comprises a bearing assembly 50 provided about the shaft 40. The bearing assembly 50 allows both reciprocating and rotating motion simultaneously, in the sense that the bearing assembly 50 allows reciprocating or translational movement of the bearing assembly 50 along the shaft 40 while allowing the shaft 40 to rotate within the bearing assembly 50. A stiffener carrier 53 is provided in the bearing assembly 50 about the shaft 40. One end of each of the stiffeners 30 is secured to the stiffener carrier 53 while the other end of each of the stiffeners 30 is free to slide within each of the hollow ribs 22.

Linear movement of the bearing assembly 50 along the shaft 40 away from the rubber pad 20 retracts the stiffeners 30 from the hollow ribs 22, while linear movement of the bearing assembly 50 along the shaft 40 towards the rubber pad 20 inserts the stiffeners 30 into the hollow ribs 22. In this way, movement of the stiffener carrier 53 controls the length of the stiffeners 30 in the channels 22 of the rubber pad 20.

As can be seen in FIGS. 5 and 6, the stiffener carrier 53 is provided with a flange bushing 52 (FIG. 7). The bearing assembly 50 may comprise a bearing housing 51 and a deep groove ball bearing 55 (FIG. 8) in addition to the stiffener carrier 53 and flange bushing 52. The flange bushing 52 is secured to the stiffener carrier 53 and the stiffeners 30 may be secured to the flange bushing 52. The flange bushing 52 and stiffener carrier 53 rotate together with the shaft 40 and can also slide linearly on the shaft. The ball bearing 55 is provided between the bearing housing 51 and the stiffener carrier 53 to allow the stiffener carrier 53 to rotate freely relative to and within the bearing housing 51. In use, the bearing housing 51 does not rotate when the rubber pad 20 is rotated. The ball bearing 55 is housed inside the stationary bearing housing 51 and secured using circlips. FIG. 9 shows the chosen components for bearing and bushings. The shaft 40 passes through the flange bushing 52 which is fixedly attached to the stiffener carrier 53. The flange bushing 52 and the stiffener carrier 53 rotate together with the shaft 40 when the rubber pad 20 is spun during polishing.

In order to smoothly slide the stiffeners 30 in and out of the hollow ribs 22, a protective tube 33 (e.g. made of nylon) may be provided over each stiffener 30 to form a tube assembly comprising the stiffener 30 and the nylon tube 33 that slides in each hollow rib 22, as shown in

FIG. 9. The protective tube 33 not only provides an additional stiffening effect, it also helps to protect the underlying soft rubber of the hollow ribs 22 from being damaged by the stiffeners 30 that may be made of steel wire. In order to reduce friction between the tube assembly and the rubber pad 20 during sliding of the stiffeners 30 within the hollow ribs 22, a lubricating oil (not shown) may be used.

In an exemplary embodiment as shown in FIG. 9, the rubber pad 20 may be provided with six hollow ribs 22 that radiate symmetrically from adjacent the geometric centre of the rubber pad 20, the hollow ribs 22 cooperating with corresponding six stiffeners 30 and six protective tubes 33 to selectably stiffen the rubber pad 20 and control compliance of the rubber pad 20 during polishing. A base diameter of the rubber pad 20 may be 72 mm. The rubber pad 20 may be made of soft rubber with shore A hardness ranging from 45 to 60, e.g. 45 ± 5 . The stiffeners 30 may comprise galvanised steel wire of 1 mm diameter. The protective tubes 33 may have an inner diameter of 2.5 mm and outer diameter of 4 mm. Appreciably, the design of the rubber pad 20 is not fixed and may be customized according to application requirements. For example, pressure change profile and material removal rate is likely to be affected by the curvature and other dimensions of the tool 10. In other embodiments, the base rubber pad 20 along with the ribs 22 may be fabricated as a single part using silicone rubber. Notably, if the material properties of the rubber pad 20 are changed, the material removal profile is subjected to change.

The stiffeners 30 are connected with the stiffener carrier 53 which in turn is connected to the bearing assembly 50. The shaft 40 is preferably made of steel. While nylon and steel wires have been chosen for use as the materials for the protective tubes 33 and the stiffeners 30 respectively in the exemplary embodiment, other types of material which facilitate the same functions may alternatively be used in other embodiments.

The rubber pad 20 and the shaft are connected 40 by attaching the rear surface 29 of the rubber pad 20 to a front end of the shaft 40. A central opening 28 may be provided at the rear surface of the rubber pad 20 for insertion of the shaft 40 therein, as shown in FIG. 9. A rear end of the shaft 40 is attachable to a spindle 60 of a polishing system 90 to rotate the tool for polishing, as shown in FIG. 10. The polishing system 90 preferably also comprises an actuator 80 to control the position of the stiffeners 30 within the channels 22. This may be achieved by the actuator 80 moving the stiffener carrier 53 provided in the bearing assembly 50 along the shaft 40 to control a distance between the bearing assembly 50 and the rubber pad 20, thereby controlling stiffness/compliance of the rubber pad 20 by controlling the relative position of the stiffeners

30 within the hollow ribs 22. A connecting rod 82 may be provided between the actuator 80 and the bearing assembly 51 to transmit linear actuation from the actuator 80 to the stiffener carrier 53, as shown in FIG. 10. The connecting rod 82 is attached to the bearing housing 51 that does not rotate during use of the tool 10, as the bearing housing 51 is isolated from the rotation of the shaft 40 by the ball bearing 55 provided between the bearing housing 51 and the stiffener carrier 53 that is attached to the shaft 40.

Fabrication And Assembly

In order to fabricate the rubber pad 20 for experimental and numerical analysis, a 3D-printed plastic mould 110 is used. The mould 110 is 3D printed along with plastic plugs 112 for creating the hollow ribs 22 in the rubber pad 20, as shown in FIG. 11. BLUESIL RTV 147 A & B silicone resin and hardener were used in a ratio of 5:1 to prepare a base or resin mixture that is used to form the rubber pad 20. Trials were carried out to arrive at this particular ratio of the resin and hardener. From the trials, it was observed that this ratio resulted in the formation of a rubber pad 20 having Shore A hardness 50 ± 5 . Before use, the mould 110 is cleaned, and the plugs 112 are placed in the mould 110 as shown in FIG. 11. Silicone rubber 113 may be provided in places in the mould 110 where spaces in the rubber pad 20 are to be formed before pouring the resin mixture into the mould 110. To form the part, the resin and hardener are mixed well in an open container, and subsequently poured into the mould 110 slowly. The resin mixture along with the mould 110 is then placed in a vacuum chamber at a temperature of about 30°C and pressure of about 40 mbar for about 5 minutes. Most of the air bubbles in the resin mixture were removed because of de-airing. The mould 110 and resin mixture are kept at room temperature for about 24 hours and allowed to cure. After curing, the part was removed from the mould 110, and the plugs 112 were removed from the removed part to obtain the rubber pad 20.

Nylon tubes 33 and steel wires 30 were cut to the desired length and placed inside the hollow ribs 22 to serve as the protective tubes 33 and stiffeners 30 respectively. The steel wires 30 were also fixed to the flange bushing 52, as shown in FIG. 12a. The stiffener carrier 53 is then secured to the flange bushing 52, and the deep groove ball bearing 55 is placed concentric to the stiffener carrier 53, as shown in FIG. 12b. This setup is then secured to the bearing housing 51 using circlips, as shown in FIG. 12c.

Static Pressure Distribution Test and Simulation

A static pressure distribution test was performed to find the pressure distribution, contact area

and the load-displacement behaviour of the tool 10. From the obtained plots, compliance change in the tool 10 can be observed. In order to check the tool compliance at different retracted positions of the stiffeners 30, instead of using an actuator 80, the stiffeners 30 were retracted or positioned manually by locking the bearing housing 51 at three different positions: 5 initial or fully inserted position at 0 mm retraction (I), half retracted position at 7.5mm retraction (Q), and completely retracted position at 15 mm retraction (R), as shown in FIGS. 13a, 13b and 13c respectively. It should be noted that polishing applications are not limited to these exemplary positions and actual polishing positions can be changed using a linear actuator 80. Displacement and contact pressure distribution were obtained at each position under two 10 different loads of 10N and 15N, using an Instron 5569 Universal Testing Machine.

The tool 10 was fixed to the 50 N load cell 210 of the universal testing machine 200 using a special jig 220 to hold the tool in the load cell 210. The jig comprised a holder 220 that included a bearing housing holder 230 that provided support for the bearing housing 51. The 15 rubber pad 20 was placed in contact with a surface of a workpiece 100 that was clamped to a lower compression plate of the universal testing machine 200. The workpiece 100 comprised an aluminium block having a top surface tilted or angled at 15° to the horizontal, as shown in FIG. 14.

20 An initial point of contact between the rubber pad 20 and the workpiece 100 was taken as zero displacement and the tool 10 was then given a downward displacement at a rate of 0.5 mm/s until the load of 15 N was registered.

For the experiments conducted, it was observed that the load-displacement response obtained 25 from each tool condition was repeatable. FIG. 16 shows the variation in the load-displacement curves for a variation in force and stiffener position. From FIG. 16, it is observed that for the stiffeners 30 in the 'I' position, the stiffness is higher, and the load-displacement curve is almost linear. This is because the entire stiffener wire 30 is fully inside the hollow rib 22, and the entire load is carried by the wire 30. For the stiffeners 30 in the 'Q' position, as indicated 30 in FIG. 16, the variation in load with displacement is uniform initially until at a displacement of 4 mm, where there was observed a sudden increase in the load. The possible reason for this sudden increase is attributed to the stiffeners 30 sharing the load. Finally, for the stiffeners 30 in the 'R' position, as also indicated in FIG. 16, there is also a linear variation of the load with displacement up to a displacement of 4.5 mm, after which there is a sudden increase in load. 35 The shift in the displacement value of the tool 10 for which this increase in load occurs is more

for the 'R' position than the 'Q' position, thus confirming that the stiffener position does significantly impact the stiffness of the tool 10.

5 In order to understand the pressure distribution and contact area, a Fujifilm pressure film 300 was used, as shown in FIGS. 15a and 15b. Initially, the films 300 were stacked together and placed on top of the surface tilted block 100. Once, the required force was reached, the tool 10 was held at the same position and the load was held for 5 seconds, after which the tool 10 was given an upward displacement until it reached the zero position. The load retaining time of 5 seconds was based on the Fujifilm catalogue for momentary pressure.

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After the tests, the films 300 were segregated according to the pressure range and later scanned using pressure mapping system. The obtained matrix is later plotted using MATLAB®. The load-displacement data obtained from this experiment is indicative of the behaviour of the tool 10 upon application of force to the tool 10 against an inclined surface 100. Furthermore, the results obtained can be compared to the load-displacement data obtained from simulations carried out on ABAQUS. In this study, load-displacement responses were obtained for the different tool conditions. The experiments were performed thrice to ensure repeatability.

20 The pressure distribution study was performed to find out the effect of stiffener position on the static pressure distribution. Three categories (2LW, 3LW, and 4LW) of Fujifilm Prescale ® pressure films were used. After the tests, the films were segregated according to the pressure range and later scanned using a pressure mapping system. The obtained matrix was later plotted using MATLAB as shown in FIGS. 17 and 18 for testing under loads of 10N and 15N respectively, at the different stiffener positions of 'I', 'Q' and 'R' as described above.

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From FIGS. 17a to 17c, it can be observed that maximum pressures of 1.01 MPa for the 'I' position, 0.501 MPa for the 'Q' position and 0.428 MPa for the 'R' position were observed. The maximum contact pressure for 'I' position is 135.98 % higher compared to 'R' position and the maximum contact pressure for 'Q' position is 101.6 % higher than 'R' position. This change in pressure is attributed to the change (reduction) in the stiffness of the rubber pad 20 by retracting the stiffeners 30. The area of contact is also observed to increase with an increase in stiffener retraction.

35 From the analysed pressure films shown in FIG. 18, maximum pressures of 1.195 MPa for the 'I' position, 0.548 MPa for the 'Q' position and 0.462 MPa for the 'R' position were observed.

This pressure variation trend is similar to the trend observed for 10 N force. The increase in the maximum pressure for 'I' compared to the 'R' position is 158.66 % and increase in pressure from 'Q' to 'I' position is 118.07 %. The area of contact is observed to increase with an increase in stiffener retraction.

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Since pressure under 0.05MPa cannot be captured using the pressure films 300, the actual contact area is calculated by applying normal paint beneath the tool 10 and pressing the rubber pad 20 against paper. Using image processing software Image J, the actual contact area is then calculated. The contact area versus stiffener retraction plot is shown in FIG. 19. From FIG. 19, it can be observed that as the stiffeners 30 are retracted away, the contact area keeps increasing for both 10N and 15N loads tested. Similarly, as the load increases for the same retracted position, the contact area for 15N is more than 10N. Similar behaviour is seen in conventional existing polishing tools.

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The prediction of contact pressure is an essential part in active compliant tool design. By conducting finite element analysis (FEA), it will be helpful not only to predict the contact pressure but also to arrive at an optimised design where desired contact pressure can be achieved. In this study, a finite element (FE) model for the assumed configuration was modelled using ABAQUS, and the FEA result was compared with the experimental values.

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Initially, the 3D models of the components such as pad 20, stiffeners 30 and workpiece 100 were imported into the ABAQUS software. In order to replicate the experiment that was carried out in the universal testing machine at lower uniform speed, 'quasi-static' analysis is more suitable. Moreover, since the tool 10 involves large deformation, 'quasi-static' analysis is more suitable than the 'general -static' analysis. In the simulation, the components are assembled as shown in FIG. 20 and 'general contact' condition is specified since contact between multiple bodies is involved. The simulation was carried out for 15N loading, as the pressure change between the 10N and 15N is almost within a difference only 0.05 MPa. In order to predict the experimental results obtained from the stiffeners 30 at the three different positions of 'I', 'Q' and 'R' as described above, the stiffeners 30 and tubes 33 in the simulation are modified by measuring the distance of the stiffener tip 31 from the rib opening 27.

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In the experiment as described above, the block 100 was fixed and the tool 10 was allowed to move. To simplify the modelling, in this case, the tool 10 was fixed and the aluminium block 100 was moved. The base of the titled aluminium block surface 100 was coupled to a reference

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point with a local axis 99, and except the loading direction, all other directions were constrained with respect to the local axis 99 as shown in FIG. 20. The shaft portion of the tool is modelled as a rigid body, and an encastered boundary condition was assigned to its reference point. Top surfaces of the tubes and stiffeners were also fixed. The rubber pad 20 and ribs 22 being made of a hyperelastic material, a quadratic hybrid three-dimensional element with a 10-node modified tetrahedron (C3D10MH) was used. For the tubes 33 and stiffeners 30, a 20-node brick element with reduced integration (C3D20R) is used, and for aluminium block, C3D8R was used.

In order to obtain the hyperelastic material property, tensile coupons were fabricated using BlueSil RTV 147 ®. The tensile tests were carried out in accordance with the ASTM D412 procedure. Stress-strain data from these tests were observed to be repeatable. Displacement data from the video extensometer was taken in this study. The obtained stress-strain values are given as material data input in the hyperelastic material model section. Subsequently, the experimental curve was evaluated for the most suitable hyperelastic model based on best fit and stability aspects as shown in FIG. 21. From FIG. 21, it is evident that the Yeoh hyperelastic material model is the most suitable of the considered hyperelastic models. Additionally, the stability information obtained from the evaluation tests confirms that this model is also stable for the given working strain range. The detailed explanation regarding Yeoh hyperelastic model is discussed in “Shahzad M, Kamran A, Siddiqui MZ, Farhan M (2015) Mechanical Characterization and FE Modelling of a Hyperelastic Material. Materials Research 18:918-924.” The workpiece 100 (E= 69 GPa), nylon tubes 33 (E=1.5 GPa) and steel wire stiffeners 30 (E=210GPa) are considered as elastic.

FIG. 22 shows the deflection of the tool 10 when pressed against the 15° inclined aluminium plate 100. As can be seen, the intensity of stresses is highest when the stiffeners 30 are completely inserted. The stress in the stiffeners 30 is found to decrease as the stiffeners 30 are retracted ('Q' and 'R' positions). The validity of the model is confirmed by checking the experimental and simulation load-displacement curves. In FIG. 22, it can be observed that in the fully inserted condition or 'I' position, the steel wire 30 is flexed along with the nylon tube 33 during the loading. The stress in the stiffeners 30 keeps decreasing as the retraction increases, indicating the role of stiffeners 30 during flexing of the tool 10 against the inclined plate 100. Subsequently, from the assigned reference point, the displacement and applied load values are obtained and compared with the experimental results.

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FIG. 23 compares the experimental and simulated load-displacement curves for the considered three stiffener retraction positions. The trend followed in the experimental data is followed in the simulation results too. From the slope of the load-displacement, it can be inferred that fully inserted stiffener condition 'I' is the stiffest and the 'R' condition is the least stiff. The variations in the load-displacement curves can be attributed to the random undulations and curvature in the bent stiffener wires 30.

The experimental and simulated contact pressure distribution was also compared, as shown in FIG. 24. The contact pressure in ABAQUS is obtained by extracting the maximum contact pressure from the initial point of loading to the final frame. The simulated maximum contact pressure values and contact area are listed in Table 1 below. It can be observed that as the retraction position increases, the maximum contact pressure keep decreasing and contact area increases reflecting the same trend followed in the experimental results. The result is compared with the pressure film results. Table 1 compares the maximum contact pressure and contact area for the simulated and experimental values. This illustrates that using such an FE model, further optimisation studies can be possibly carried out to arrive at the desired design and material parameters.

Position	Maximum static contact pressure (MPa)		Static contact area (mm ²)	
	Experimental	Simulation	Experimental	Simulation
I	1.195	1.239	292	264
Q	0.548	0.559	419.701	412
R	0.462	0.491	437.377	466

Table 1 Experimental and simulation values for maximum contact pressure and contact area for static tests

The maximum contact pressure is a key parameter of interest as it directly related to the maximum material removal depth. Comparing values from FIG. 18 and FIG. 24, it can be observed that the maximum pressure values match well with the simulation results. Using the current numerical models, optimisation studies can be carried out to improve the tool design and proper materials selection to increase the contact pressure variation for different stiffener retraction positions.

Machining Experiments and Simulation

Machining trials were carried out using the fabricated tool 10 to check the effect of tool compliance on the material removal depth and contact area. The experimental trials were carried out using a MIKROTOOLS DT-110 Multi-Process Micro Machining system as shown in FIG. 25. A dynamometer 251 with data acquisition is placed under the workpiece 100 to monitor the force exerted by the tool on the workpiece 100 at the time of machining. The dynamometer 251 helps to confirm that a constant force was maintained for the 3 seconds of machining time used during the trials. Since the machine is not equipped with a force-controlled system, z-axis displacement was fixed such that the required force is maintained during machining.

In the experimental setup, the tool 10 was clamped in the jig comprising a tool holder 220, as shown in FIG. 25b. Clamps and thin aluminium plates 222 of 20 mm width, with a 7 mm slot running along the middle, were used to align the bearing housing 51 and the tool holder 220. The bearing housing 51 was clamped on both sides by these slotted aluminium plates 222. This helped to minimize vibration and to ensure that the bearing housing 21 was held stationary at all times during operation of the tool 10. The workpiece 100, a rectangular plate of 152 mm x 90 mm x 3 mm was used. Since tilting the entire tool setup is complex in this case, the workpiece 100 was tilted instead. The workpiece 100 was mounted on an aluminium block with a 15° surface tilt. A 3M® 216U Paperback Abrasive Disc with #120 was used as the abrasive pad for the tool 10. Discs of 80 mm diameter were cut out and secured to the base 21 of the tool 10 using adhesive tape.

The experimental trials were carried out in the above described three positions ('I', 'Q', 'R') for 10N and 15N normal force at a spindle speed of 1000 RPM. After machining, the samples 100 were cleaned, and the three-dimensional surface data information was acquired by scanning the surface using a laser probe in a TalyScan® profilometer to obtain the 3D material removal data. Using the software, information like maximum depth, depth variation, contact area and volume of material removal is estimated and investigated for the different experimental conditions.

As can be seen from the material removal profiles in FIG. 26, significant variation in the depth of material removal profile was observed with a variation in the position of the stiffeners 30 under a test load of 10N. The increase in material removal depth from the half retracted (Q) position to the stiffeners 30 in the fully inserted (I) is observed to be 41.23%. The maximum

increase in material removal depth from completely retracted (R) to fully inserted (I) condition is 85.5%. The effect of retraction of the stiffeners 30 is reflected in the machined area too. As the retraction increases, the machined area increases too.

- 5 From the experiments carried out for a tool force of 15 N, a similar variation in the depth of material removal was observed with a variation in the position of the stiffeners 30, as shown in FIG. 27. The increase in material removal depth from the half retracted (Q) position to the stiffeners in the fully inserted (I) is observed to be 40.16%. The maximum increase in material removal depth from completely retracted (R) to fully inserted (I) condition is 84.5%. A similar
10 effect of retraction on the machined area as observed with 10N tool force above is also observed with 15N tool force.

- From FIGS. 26 and 27, it can be observed visually that the contact area kept increasing as the stiffener retraction is increased. It can be visually observed that the contact area increases
15 while the maximum depth of material removal decreases due to the increased retraction of the stiffeners 30.

- From FIGS. 28 and 29, it can be observed that the stiffeners 30 at each retraction position indeed have an effect on the material removal depth and the machined area of the tool. The
20 larger contact area and lower material removal depth observed with increased stiffener retraction mimic a conventional soft tool, and the smaller contact area and higher material removal depth observed with reduced stiffener retraction reflect the nature of a conventional hard rubber tool. Thus, the novel tool 10 shows that it can be a potential replacement for conventional compliant tools.

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Integration with Linear Actuator

- As mentioned above, the tool 10 may be incorporated into a polishing system 90 that comprises a linear actuator 80 provided to selectably move the stiffener carrier 53 provided in the bearing assembly 50 along the shaft 40 to control a distance between the stiffener carrier 53
30 and the rubber pad 20, thereby controlling compliance of the rubber pad 20 by controlling the relative position of the stiffeners 30 within the hollow ribs 22. The linear actuator 80 may be integrated with the polishing tool 10 using an open-loop control system. The key components of this open-loop control system are an Arduino board 300, control buttons, joystick and a linear actuator 80. The actuator 80 can be controlled either through the control buttons (using
35 pre-set positions) or directly through the Arduino code with which the Arduino board 300 is

programmed.

Polishing trials were carried out using the polishing system 90 by mounting the polishing system 90 comprising the tool 10 and actuator 80 in a CNC milling machine, as shown in FIG. 30. Under a load of 10N at the three different stiffener positions 'I', 'Q' and 'R' as described above ('I', 'Q' and 'R' positions corresponding to completely inserted, half-way retracted and completely retracted positions respectively) that replicate the three levels of compliances available in conventional backing pads, polishing trials were carried out by making linear passes on a workpiece 100 at the three different stiffener positions at a spindle speed of 2000RPM and with a feed rate of 10 mm/s. A dynamometer 251 with data acquisition was placed under the workpiece 100 to monitor the force exerted by the tool 10 on the workpiece 100 at the time of machining, as shown in FIG. 30.

While FIG. 30 shows the tool 10 in a vertical position, during the polishing trials, the tool 10 was tilted at 15° and pressed against the workpiece 100, as shown in FIG. 31. After machining one pass in the 'I' position (FIG. 31a), the workpiece 100 was changed, and using the control button, the actuator 80 was retracted to the 'Q' position (FIG. 31b). Since force control option is not available, relevant downward-displacement is given through the CNC program to maintain the force approximately at a constant level of 10N, for all cases. Carrying out the retractions in a single pass is not feasible with the position-controlled CNC machine, as when the stiffener carrier 53 is retracted for the same downwards displacement, the force applied will change.

The material removal depth in the machined samples was measured using a Talyscan® profilometer. The material removal depth was measured perpendicular to the direction of the tool pass and the profile for the different stiffener positions. The extracted 2D material removal profiles were levelled and plotted using MATLAB®. Trials were repeated for each stiffener position to ensure the repeatability of the values. The measured data for the three different stiffeners positions are shown in FIG. 32. It is evident from FIG. 32 that the position of the stiffeners 30 alters the material removal depth. The average material removal depths are 22.6µm, 14.8µm and 11.8µm for the 'I' (completely inserted), 'Q' (mid position) and 'R' (completely retracted) positions respectively. The maximum material removal depth is observed in the case of completely inserted stiffeners 30 and vice-versa. The material removal depth is dependent on the rubber tool material and the stiffener materials.

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Robotic Polishing Trials

Robotic polishing trials using the above described polishing system 90 were performed on a curved aluminium sample 100 by attaching the system 90 to an ABB 140 6-axis robot 400 that was programmed to allow the tool 10 to follow the curved aluminium profile of the sample block, whilst maintaining a 15° tool tilt angle and applying a constant force of 10N, as shown in FIG. 33. The tool 10 was tested with stiffeners 30 in the fully inserted 'I' and fully retracted 'R' positions.

To study the effects of tool configuration on a curved surface, experiments were carried out whilst the tool 10 was in the fully inserted and retracted stiffener positions, as shown in FIG. 34. The trials were conducted thrice in each configuration, to ensure a constant and reliable data for analysis. Once testing was complete, the curved aluminium blocks were placed on the Talyscan® profilometer and using the same procedure to measure initial surface roughness, the polished surfaces were profiled. The measurements were focused on the curved portion of the aluminium block.

FIG. 35 shows superimposed profiles of the curved surfaces polished with the tool having stiffeners in the fully inserted and fully retracted positions. From an analysis of FIG. 34, it can be observed that there is a clear difference in the depth of material removal on the curved surface.

From the above-described experiment, it can be concluded that the actuator 80 was successful in inserting and retracting the stiffeners 30 during the polishing operations. This proves that without changing the tool 10 each time, the compliance in the presently described polishing tool 10 can be changed while machining. From the profilometer measurements of the machined samples, it was observed that the fully inserted stiffeners 30 gave maximum material removal, followed by midway retracted stiffeners 30 and completely retracted stiffeners giving midway and minimum material removal respectively. The experimental results show that the tool 10 works on curves with a large radius, and that the configuration of the tool (i.e. position of the stiffeners 30 relative to the rubber pad 20) will impact the depth of material removal on a curved surface. This proves that adjustable tool compliance has a desirable effect on material removal for both flat and curved surfaces.

Whilst there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many

variations and combination in details of design, construction and/or operation may be made without departing from the present invention. For example, while the channels in the rubber pad have been described above as being in the form of hollow ribs provided on a rear surface of the rubber pad, in other configurations, the channels may be provided under the rear surface of the rubber pad such that the rubber pad comprises no visible ribs. Alternatively, the channels may comprise hollow ribs that are separately formed from the rubber pad as flexible tubes and subsequently attached to the rear surface of the rubber pad. While the stiffeners have been described above and depicted in the figures as comprising steel wires or having circular cross-sections, the stiffeners may have other cross-sectional shapes, e.g. the stiffeners may comprise strips of material of rectangular or oval cross-section. In alternative embodiments, each stiffener may comprise more than one wire. While the channels have been depicted as lumen having circular cross-sections, the channels may alternatively have other cross-sectional shapes that correspond with the cross-sectional shapes of the stiffeners. While the stiffeners have been described and depicted as being attached to the flange bushing of the stiffener carrier, in other embodiments, the stiffeners may be attached to another part of the stiffener carrier. While the channels are shown in the figures to extend to an outer edge the outer diameter of the rubber pad, in other embodiments, the channels may terminate before the outer edge of the rubber pad.

CLAIMS

1. A polishing tool comprising:
 - a rubber pad provided with a number of channels; and
 - 5 a corresponding number of stiffeners receivable in the channels to slidably engage the channels;
 - wherein increase in length of the stiffeners in the channels increases stiffness and decreases compliance of the rubber pad.
- 10 2. The polishing tool of claim 1, wherein the rubber pad is provided at one end of a shaft configured to be attached to a spindle, and wherein one end of each of the stiffeners is secured to a stiffener carrier provided about the shaft.
- 15 3. The polishing tool of claim 2, wherein the stiffener carrier is provided with a flange bushing, the flange bushing allowing linear movement of the stiffener carrier along the shaft, the flange bushing and stiffener carrier rotating together with the shaft when the shaft is rotated by the spindle.
- 20 4. The polishing tool of claim 3, further comprising a bearing assembly, the bearing assembly comprising a bearing housing and a bearing provided about the shaft, the bearing provided between the bearing housing and the stiffener carrier to allow rotation of the stiffener carrier relative to the bearing housing.
- 25 5. The polishing tool of any one of the preceding claims, wherein the channels comprise hollow ribs provided on a rear surface of the rubber pad.
6. The polishing tool of claim 5, wherein the hollow ribs are integrally formed with the rubber pad.
- 30 7. The polishing tool of any one of the preceding claims, wherein the channels have channel openings adjacent a geometric centre of the rubber pad, the stiffeners entering the channels at the channel openings.
- 35 8. The polishing tool of any one of the preceding claims, wherein the channels radiate symmetrically from adjacent the geometric centre of the rubber pad.

9. The polishing tool of any one of the preceding claims, wherein the channels extend to an outer edge of the polishing pad.
- 5 10. The polishing tool of any one of the preceding claims, further comprising a protective tube provided around each stiffener within the channels.
11. The polishing tool of any one of the preceding claims, wherein the protective tube is made of nylon.
- 10 12. The polishing tool of any one of the preceding claims, wherein the stiffeners comprise steel wires.
13. A polishing system comprising:
- 15 the polishing tool of any one of the preceding claims; and
a linear actuator to control position of the stiffeners within the channels.
14. The polishing system of claim 13 when dependent on any one of claims 2 to 4 and any one of claims 5 to 12 when dependent on any one of claims 2 to 4, further comprising a
- 20 connecting rod provided to transmit linear actuation from the linear actuator to the stiffener carrier.
15. A rubber pad for a polishing tool, the rubber pad comprising:
- 25 a number of channels to slidably engage a corresponding number of stiffeners received therein,
wherein increase in length of the stiffeners in the channels increases stiffness and decreases compliance of the rubber pad.
16. The rubber pad of claim 15, wherein the channels comprise hollow ribs provided on a rear
- 30 surface of the rubber pad.
17. The rubber pad of claim 15 or 16, wherein the hollow ribs are integrally formed with the rubber pad.
- 35 18. The rubber pad of any one of claims 15 to 17, wherein the channels have channel openings

adjacent a geometric centre of the rubber pad.

19. The rubber pad of any one of claims 15 to 18, wherein the channels radiate symmetrically from adjacent the geometric centre of the rubber pad.

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20. The rubber pad of any one of claims 15 to 19, wherein the channels extend to an outer edge of the polishing pad.