

METHOD FOR FINISHING COMPLEX SHAPES IN WORKPIECES

TECHNICAL FIELD

The following is directed to abrasive tools and methods of finishing complex shapes in workpieces using such abrasive tools, and more particularly, use of grinding tools for finishing of complex shape openings within workpieces.

BACKGROUND ART

Within the industry of finishing, various processes may be employed to finish workpieces. However, in the particular context of finishing workpieces to have complex shapes, few options are available since such finishing operations require exacting surface contours and tight dimensional tolerances. Certain preferred approaches are milling or broaching, where blades are used to cut the complex shape in the workpiece. However, broaching can be an expensive operation, due to high tooling costs, expensive machinery, set-up costs, tooling regrinding costs and slow material removal rates. Milling processes are generally very slow, especially in machining difficult-to-machine materials, such as nickel alloys.

Still, in the context of forming retention slots in turbine disks, which are used to hold or retain turbine blades around the periphery of the disk, broaching is the preferred approach throughout most of the industry. Current practice in the aerospace industry is to machine slots into the disk by use of a broaching machine, which is a linear cutting machine that drives successively larger cutters through the disk slot, with the final cutters having a desired complex shape (i.e., a re-entrant shape) of the finished slot. Broaching is illustrated in U.S. Pat. No. 5,430,936 to Yadzik, Jr. et al.

Another method for producing profiled parts is illustrated in U.S. Pat. No. 5,330,326 to Kuehne et al. The method involves pre-shaping and finish grinding a blank in one chucking position with at least one profiled grinding wheel. The blank is translated and rotated relative to the at least one profiled grinding wheel during the pre-shaping step for giving the blank approximately a desired profile. However, the Kuehne method may be used for external surfaces, and not internal surfaces, and thus is not applicable to the creation of internal slots.

Other methods of producing complex shapes in workpieces are disclosed in U.S. Pat. No. 6,883,234 and U.S. Pat. No. 7,708,619. In U.S. Pat. No. 7,708,619 to Subramanian et al., the processes utilizes grinding with a large diameter wheel operated perpendicular to the surface of the part for initial formation of a slot within the workpiece. Finishing of the slot to the desired contour is completed using a single-layered electroplated tool.

There is a need to develop new methods to form complex shapes within workpieces and limit the shortcomings associated with conventional processes.

SUMMARY

According to a first aspect, a method of forming a complex form in a workpiece includes moving a grinding tool having a complex shape relative to a surface of a workpiece to form a complex shape opening in the workpiece, wherein the grinding tool is tilted in a lateral plane relative to the workpiece.

In another aspect, a method of forming a complex form in a workpiece includes moving a grinding tool having a complex shape relative to a side surface of a rough slot in a workpiece to form at least a portion of a complex shape opening in a first side of the rough slot, wherein during moving, a bottom surface of the grinding tool is spaced apart from a bottom surface of the rough slot.

In yet another aspect, a method of forming a complex form in a workpiece includes moving a grinding tool having a complex shape relative to a surface of a workpiece to form a complex shape opening in the workpiece, wherein the grinding tool is tilted in a lateral plane relative to the workpiece, and wherein a bottom surface of the workpiece is formed to have a substantially convex curvature.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure may be better understood, and its numerous features and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

FIG. 1 includes a schematic representation of a rough slot formation process in accordance with an embodiment.

FIGS. 2(a) and 2(b) include schematic representations of rough slots that can be generated by the rough slot formation process.

FIG. 3 includes an illustration of a process of moving a grinding tool to form a complex shape opening in a workpiece according to an embodiment.

FIG. 4 includes a cross-sectional illustration of a grinding tool having a complex shape according to an embodiment.

FIG. 5 includes an illustration a process of moving a grinding tool to form a complex shape opening in a workpiece according to an embodiment.

FIG. 6 includes an illustration of a process of moving a grinding tool to form a complex shape opening in a workpiece according to an embodiment.

FIG. 7A includes an illustration of a portion of a complex shape opening in a workpiece according to an embodiment.

FIG. 7B includes an illustration of a portion of a complex shape opening in a workpiece according to an embodiment.

The use of the same reference symbols in different drawings indicates similar or identical items.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The following is directed to methods of using particular grinding tools, including grinding tools having a complex shape, which may be used to form complex shape openings in workpieces. In at least one embodiment, the grinding tool can be a bonded abrasive tool suitable for forming and/or finishing of surfaces of a workpiece. It will be appreciated that bonded abrasives are a separate and distinct class from other abrasives (e.g. coated abrasives, etc.) in that bonded abrasives have a three-dimensional shape including a dispersion of abrasive particles throughout a three-dimensional volume, which are contained within a three-dimensional volume of bonding material. Moreover, bonded abrasive bodies may include some amount of porosity, which may facilitate chip formation and exposure of new abrasive particles. Chip formation, abrasive grain exposure, and dressing are certain attributes associated with bonded abrasives, and which distinguish bonded abrasives from other classes of abrasives, such as coated abrasives or single layer electroplated tools.

As used herein, the term "complex shape" refers to a shape (e.g., of an opening within a workpiece) or a shape of a part (e.g., a body of a grinding tool) that can have a curved contour defining a combination of concave and convex curvatures. In at least one embodiment, a complex shape can include a contour defining a re-entrant shape. A re-entrant shape does not allow a mating form to be removed in a direction normal to one of three axes (i.e., x, y or z). A "re-entrant shape" can be a contour that is re-entering or pointing inward, which is wider at an inner axial position than at an outer axial position (i.e., an entrance). An example of the re-entrant shape is a dovetail slot, a keystone shape, and the like.

The advanced grinding processes described herein may be utilized in a variety of industries, including for example, construction, mining, aeronautics, naval architecture and construction, advanced machining applications, and the like. In particular instances, turbine components, such as jet engine, rotors, compressor blade assembly, typically employ re-entrant shaped slots in the turbine disks. The re-entrant shape can be used to hold or retain turbine blades around the periphery of turbine disks. Mechanical slides, T-slots to clamp parts on a machine table also use such re-entrant shaped slots.

With respect to a process of forming a complex shape in a workpiece, an initial slot or rough slot formation process can be undertaken, which forms an opening within the workpiece. The rough slot does not necessarily have the desired final contour (i.e., complex shape). The rough slot formation process can remove the bulk of material, minimizing the amount of material to be removed in the complex shape finishing process with a bonded abrasive tool. As such, in one embodiment, the process can first utilize further comprising forming a rough slot in the workpiece prior to moving the grinding tool.

FIG. 1 includes an illustration of a slot formation process 10. As illustrated, the rough slot formation process can utilize a bonded abrasive tool 12, oriented in a particular manner with respect

to the workpiece 14, thereby forming rough slot(s) 16 in workpiece 14. In a particular embodiment, the rough slot formation processes of the invention can be completed using a bonded abrasive tool 12 oriented with respect to the workpiece 14 to conduct a creep-feed grinding process. The creep-feed grinding can be conducted at grinding speed in a range between about 30 m/s and about 150 m/s. For example, the process of forming a rough slot can include rotating a grinding wheel having a generally annular shape against a portion of the workpiece to form the rough slot.

FIGS. 2(a) and 2(b) include schematic representations of slots that can be generated by the rough slot formation process. In particular, FIGS. 2(a) and 2(b) include workpieces 18A and 18B that can be formed by the rough slot formation processes 10 of the invention, respectively. In one embodiment, rough slot 16 can have a single diameter throughout the depths of the slot 16, as shown in FIG. 2(a). In another embodiment, slot 16 has at least two distinct diameters at different depths, as shown in FIG. 2(b). In one particular embodiment, the rough slot 16 can have a simple shape, such as one or a combination of polygonal shapes, and more particularly, an opening width at the exterior 21 of the workpiece that is the same or greater than the opening width at the bottom 23 of the rough slot 16. According to one particular embodiment, the rough slot 16 can have a non-complex shape, which can be the opposite of a complex shape. Moreover, in certain instances, the rough slot 16 can have a generally rectangular cross-sectional shape as viewed in a lateral plane of the workpiece, such as the generally planar surface 25 of the workpiece 14.

The rough slot formation process may utilize a particular specific cutting energy. For example, the specific cutting energy may be equal to, or less than, about 10 Hp/in³ min (about 27 J/mm³), such as between about 0.5 Hp/in³ min (about 1.4 J/mm³) and about 10 Hp/in³ min (about 27 J/mm³) or between about 1 Hp/in³ min (about 2.7 J/mm³) and about 10 Hp/in³ min (about 27 J/mm³).

In another embodiment, the rough slot formation process can be conducted at a particular material removal rate (MRR), such as in a range of between about 0.25 in³/min in (about 2.7 mm³/sec/mm) and about 60 in³/min in (about 650 mm³/sec/mm) at a maximum specific cutting energy of about 10 Hp/in³ min (about 27 J/mm³).

The rough slot formation process as well as the complex shape grinding and finishing processes of the embodiments herein can be completed on certain types of workpiece materials, including hard-to-grind materials. The workpieces of the embodiments herein can be metallic, and particularly metal alloys such titanium, Inconel (e.g., IN-718), steel-chrome-nickel alloys (e.g., 100 Cr6), carbon steel (AISI 4340 and AISI 1018) and combinations thereof. In accordance with one embodiment, the workpiece can have hardness value of equal to or less than about 65 Rc, such as between about 4 Rc and about 65 Rc (or 84 to 111 Rb hardness). This is in contrast to prior art machining processes that typically can be used only for softer materials, i.e., those having a maximum hardness value of about 32 Rc. In one embodiment, the metallic workpieces for the invention have a hardness value of between about 32 Rc and about 65 Rc or between about 36 Rc and about 65 Rc.

In the rough slot formation process, a bonded abrasive tool can be used, such as grinding wheels and cutoff wheels. The bonded abrasive tool for use in the rough slot formation process can include at least about 3 volume % (on a tool volume basis) of a filamentary sol gel alpha-alumina abrasive grain, optionally including secondary abrasive particles or agglomerates thereof. Suitable bonded abrasive tools are disclosed in U.S. Pat. Nos. 5,129,919; 5,738,696; 5,738,697; 6,074,278; and 6,679,758 B, and U.S. patent application Ser. No. 11/240,809 filed Sep. 28, 2005, the teachings of which are incorporated herein by reference. Particular details of the bonded abrasive tool used in the slot forming process are provided in U.S. Pat. No. 7,708,619, the teachings of which are incorporated herein by reference.

Referring now to operations following the rough slot formation process, a process of moving a grinding tool having a complex shape relative to a surface of the workpiece may be undertaken to form at least a portion of the rough slot into a complex shape opening. In particular instances, the process of moving the grinding tool having a complex shape can include and be referred to herein as a grinding process, a finishing process, and a combination thereof. More particularly, the process of moving the grinding tool having a complex shape relative to the rough slot can be conducted to change the contour of the rough slot to a complex shape (e.g., re-entrant shape). The grinding tools used to conduct the slot formation and the finishing process can be part of high efficiency grinding machines, including multi-axis machining centers. With a multi-axis machining center, both the slot formation and the complex shape finishing process can be carried out on the same machine. Suitable grinding machines include, e.g., a Campbell 950H horizontal axis grinding machine tool, available from Campbell Grinding Company, Spring Lake, Mich., and a Blohm Mont. 408, three axis, CNC creep feed grinding machine, available from Blohm Maschinenbau GmbH, Germany.

FIG. 3 includes an illustration of a process of moving a grinding tool having a complex shape relative to a portion of a workpiece in accordance with an embodiment. In particular, FIG. 3 illustrates a grinding or finishing operation to form a complex shape within the slot 16 of the workpiece 14 with a grinding tool 301. The grinding tool 301 may be a grinding quill tool, and more particularly, may be a mounted point tool. The grinding tool 301 can have a body 303 including a bonded abrasive body having a complex shape suitable for producing a complex shape within the workpiece 14. That is, the bonded abrasive body 303 can have a shape that is the inverse of a complex shape, to be imparted into the workpiece 14.

More notably, in at least one embodiment, the bonded abrasive body 303 can have a first complex shape that is configured to form a second complex shape in the workpiece 14. As will be described herein in more detail, the grinding tool 301 may be operated in a particular manner with respect to the workpiece 14, and the orientation utilized by the grinding tool 301 relative to the workpiece 14 during the material removal operation may facilitate utilization of a bonded abrasive body 301 having a first complex shape that is different than the complex shape formed in the

workpiece. Notably, the difference in the contour between the first complex shape and the second complex shape may be significant to facilitate a suitable finally-formed second complex shape in the workpiece 14.

In accordance with embodiments herein, the grinding tool 301 can have a bonded abrasive body 303 including abrasive particles contained within a matrix of bonding material. That is, the bonded abrasive body 303 can have abrasive particles dispersed throughout a three-dimensional matrix of bonding material. In accordance with an embodiment, the abrasive particles can include superabrasive materials. For example, suitable superabrasive materials can include cubic boron nitride, diamond, and a combination thereof. In certain instances, the bonded abrasive body 303 can include abrasive particles that consist essentially of diamond. However, in other tools, the bonded abrasive body 303 can include abrasive particles that consist essentially of cubic boron nitride.

The bonded abrasive tool can be formed such that it has an abrasive body incorporating abrasive particles having an average particle size of not greater than about 150 microns. In some embodiments, the abrasive particles can have an average particle size of not greater than about 125 microns, such as not greater than about 100 microns, or even not greater than about 95 microns. In one non-limiting embodiment, the abrasive particles can have an average particle size of at least about 1 micron, such as at least about 10 microns, at least about 15 microns, at least about 20 microns, or even at least about 30 microns. It will be appreciated that the abrasive particles can have an average particle size within a range between any of the minimum and maximum values noted above.

With regard to the bonding material within the bonded abrasive body 303, suitable materials can include organic materials, inorganic materials, and a combination thereof. For example, suitable organic materials may include polymers such as resins, epoxies, and the like.

Some suitable inorganic bond materials can include metals, metal alloys, ceramic materials, glass materials, and a combination thereof. For example, some suitable metals can include transition metal elements and metal alloys containing transition metal elements. In other embodiments, the bond material may be a ceramic material, which can include polycrystalline and/or vitreous materials. Suitable ceramic bonding materials can include oxides, including for example, SiO_2 , Al_2O_3 , B_2O_3 , MgO , CaO , Li_2O , K_2O , Na_2O and the like.

Further, it will be appreciated that the bonding material can be a hybrid material. For example, the bonding material can include a combination of organic and inorganic components. Some suitable hybrid bond materials can include metal and organic bond materials.

In accordance with at least one embodiment, the bonded abrasive body 303 can include a composite including bond material, abrasive particles, and some porosity. For example, the bonded abrasive body 303 can have at least about 2 vol% abrasive particles (e.g., superabrasive particles) of the total volume of the bonded abrasive body. In other instances, the bonded abrasive body 303 can include at least about 6 vol%, at least about 10 vol%, at least about 15 vol%, at least about 20 vol%,

or even at least about 25 vol% abrasive particles. In one non-limiting embodiment, the bonded abrasive body 303 can include not greater than about 65 vol%, such as not greater than about 60 vol%, or even not greater than about 55 vol% superabrasive particles. It will be appreciated that the content of abrasive particles in the bonded abrasive body 303 can be within a range between any of the minimum and maximum values noted above.

The bonded abrasive body 303 can be formed to have at least about 2 vol% bond material (e.g., vitrified bond or metal bond material) of the total volume of the bonded abrasive body 303. In other instances, the bonded abrasive body 303 can include at least about 6 vol%, at least about 10 vol%, at least about 15 vol%, at least about 20 vol%, or even at least about 25 vol% bond material. In one non-limiting embodiment, the bonded abrasive body 303 can include not greater than about 65 vol%, such as not greater than about 60 vol%, or even not greater than about 55 vol% bond material. It will be appreciated that the content of bond material in the bonded abrasive body 303 can be within a range between any of the minimum and maximum values noted above.

The bonded abrasive body 303 can be formed to have a certain content of porosity, and particularly, an amount of not greater than about 60 vol% of the total volume of the bonded abrasive body 303. For example, the bonded abrasive body 303 can have not greater than about 55 vol%, such as not greater than about 50 vol%, not greater than about 45 vol%, not greater than about 40 vol%, not greater than about 35 vol%, or even not greater than about 30 vol% porosity. In one non-limiting embodiment, the bonded abrasive body 303 can include at least about 0.5 vol%, at least about 1 vol%, at least about 1.5 vol%, at least about 2 vol%, or even at least about 2.5 vol% porosity. It will be appreciated that the content of porosity in the bonded abrasive body 303 can be within a range between any of the minimum and maximum values noted above.

During the material removal process using the grinding tool 301, the bonded abrasive body can be placed in contact with the workpiece 14, and more particularly within the rough slot 16 previously formed within the workpiece 14. In accordance with an embodiment, the bonded abrasive body can be rotated at a significantly high speed to finish and re-contour at least a portion of the surface of the rough slot 16. For example, the bonded abrasive body 303 can be rotated at high speeds and contacted to at least a portion of the side surfaces 321 and/or 323 of the slot 16 to form a complex shape opening within the workpiece 14. For example, the grinding tool 301, and thus the bonded abrasive body 303, can be rotated at speeds of at least about 10,000 rpm. In other instances, the tool may be rotated at greater speeds, such as at least about 20,000 rpm, at least about 30,000 rpm, at least about 40,000 rpm, or even greater. Still, in certain instances the grinding tool 301 can be rotated relative to the workpiece 14 at a speed of not greater than about 250,000 rpm, such as not greater than about 125,000 rpm, not greater than about 110,000 rpm, or even not greater than about 100,000 rpm. It will be appreciated that bonded abrasive tool can be rotated at a speed within a range between any of the minimum and maximum values noted above.

During finishing, the grinding tool 301 can be moved along a particular pathway relative to the workpiece 14 to facilitate finishing of at least a portion of the side surfaces 321 and 323 to a suitable, complex shape. For example, in certain instances the grinding tool 301 can follow a reciprocating pathway or complete a box cycle. For example, in a first pass of the reciprocating pathway, the bonded abrasive tool 300 can be moved relative to the workpiece 14 along a path 310. Movement of the grinding tool 301 along the path 310 can facilitate contact of the bonded abrasive body 303 with at least a portion of the side surface 321 to remove material from the side surface 323 and form at least a portion of a complex shape opening 306. According to one type of reciprocating pathway, after completing the first pass along path 310, the grinding tool 301 can be shifted laterally and moved along a path 311 in a second pass.

According to one reciprocating pathway, during the second pass, the surface of the grinding tool 301 can contact at least a portion of the side surface 321 of the slot 16 opposite the side surface 323, and thereby finishing the portion of the slot 16 defined by the surface 323 and form a complex shape opening 306. After the grinding tool 301 travels along the full thickness of the workpiece through the slot 16, the tool can then again be shifted laterally and returned to the path 310 for another (i.e., third) pass along the surface 323. It will be appreciated that the grinding tool 301 may be reciprocated and moved along paths 310 and 311 for a designated number of turns until the surfaces 321 and 323 are satisfactorily finished. It will further be appreciated that while the paths 310 and 311 are illustrated as being linear, certain processes can utilize paths that are curved or utilize an arced direction.

According to an alternative embodiment, the pathway of the grinding tool 301 can be altered such that one side surface of the slot 16 can be finished to have a complex shape or a portion of the complex shape before another side surface is finished to have a complex shape or define a portion of the complex shape. For example, the grinding tool 301 can be moved along the side surface 323 for multiple, sequential passes (i.e., back and forth along path 310) until the side surface 323 is finished with a suitable complex shape. After finishing the side surface 323, the bonded abrasive tool can be shifted laterally to contact the side surface 321 opposite the side surface 323. The grinding tool 301 can then again be moved along the thickness of the slot 16 (i.e., back and forth along the path 311) along the second surface 321 for multiple, sequential passes until the side surface 321 is finished.

In accordance with one embodiment, the material removal process may remove a particular amount of material from the surface of the slot on each pass. For example, during material removal, the grinding tool 301 may remove material from any one of the side surfaces to a depth of not greater than 100 microns for each pass of the grinding tool 301 through the slot 16. In other embodiments, the material removal operation may be conducted such that the material is removed to a depth of not greater than about 75 microns, such as not greater than about 65 microns, such as not greater than about 50 microns, or even less for each pass of the grinding tool 301 through the slot 16. In particular

instances, each pass of the grinding tool 301 may remove material to a depth within a range between 1 micron and about 100 microns, such as between about 1 micron and about 75 microns, or even between about 10 microns and about 65 microns.

Moreover, during material removal, the feed rate of the bonded abrasive tool, which is a measure of the lateral movement of the bonded abrasive tool along the lateral axis 375 between sequential passes at the same surface, can be at least about 30 ipm [762 mm/min]. In other embodiments, the feed rate can be greater, such as at least about 50 ipm [1270 mm/min], at least about 75 ipm [1905 mm/min], at least about 100 ipm [2540 mm/min], or even at least about 125 ipm [3175 mm/min]. Certain finishing processes utilize a feed rate within a range between about 30 ipm [762 mm/min] and about 300 ipm [7620 mm/min], such as between about 50 ipm [1270 mm/min] and about 250 ipm [6350 mm/min], or even within a range between about 50 ipm [1270 mm/min] and about 200 ipm [5080 mm/min].

The material removal operation to form the re-entrant shape in the workpiece may be conducted at specific material removal rates. For example, the material removal rate during the material removal operation can be at least about 0.01 inches³/min/inch [0.11 mm³/sec/mm]. In other instances, the material removal process can be conducted at a material removal rate of at least about 0.05 inches³/min/inch [0.54 mm³/sec/mm], such as at least about 0.08 inches³/min/inch [0.86 mm³/sec/mm], at least about 0.1 inches³/min/inch [1.1 mm³/sec/mm], at least about 0.3 inches³/min/inch [3.2 mm³/sec/mm], at least about 1 inch³/min/inch [11 mm³/sec/mm], at least about 1.5 inches³/min/inch [16 mm³/sec/mm], or even at least about 2 inches³/min/inch [22 mm³/sec/mm].

For certain operations, the material removal rate can be not greater than about 1.5 inches³/min/inch [16 mm³/sec/mm]. Still, certain material removal processes may have a material removal rate of not greater than about 1 inch³/min/inch [11 mm³/sec/mm], not greater than about 0.8 inches³/min/inch [8.6 mm³/sec/mm], or even not greater than about 0.3 inches³/min/inch [3.2 mm³/sec/mm].

In particular instances, the finishing process can be conducted such that the material removal rate can be within a range between about 0.01 inches³/min/inch [0.11 mm³/sec/mm] and about 2 inches³/min/inch [22 mm³/sec/mm], such as between about 0.03 inches³/min/inch [0.32 mm³/sec/mm] and about 1.5 inches³/min/inch [16 mm³/sec/mm].

The material removal operation in accordance with embodiments herein may further be conducted at a particular material removal power. For example, the material removal power used during the operation can be not greater than about 5 Hp [3.75 kW] at a feed rate of the mounted point tool within a range between about 30 ipm [762 mm/min] and about 300 ipm [7620 mm/min]. According to certain other embodiments, during the material removal power can be not greater than about 4 Hp [3.0 kW], such as not greater than about 3.8 Hp [2.83 kW], not greater than about 3.6 Hp [2.68 kW], not greater than about 3.4 Hp [2.54 kW], not greater than about 3.2 Hp [2.39 kW], or even

not greater than about 3 Hp [2.25 kW]. Such material removal power may be used at a feed rate of the within a range between about 30 ipm [762 mm/min] and about 300 ipm [7620 mm/min].

It will also be appreciated that the material removal operation may be distinct from other material removal operations in that the surface of the workpiece upon completion of the operation can have particular characteristics. For example, the side surfaces 321 and 323 can have a surface roughness (R_a) of not greater than about 2 microns. In other instances, the surface roughness (R_a) may be less, such as not greater than about 1.8 microns, such as not greater than about 1.5 microns. In particular instances, the surface roughness (R_a) of the side surfaces 321 and 323 after completing the material removal process can be within a range between about 0.1 microns and about 2 microns. The surface roughness of the finished side surfaces 321 and 323 can be measured using a Profilometer, such as a MarSurf UD 120/LD 120 model Profilometer, commonly available from Mahr-Federal Corporation, and operated using MarSurf XCR software.

Upon completion of the operation, the side surfaces 321 and 323 defining the complex shape opening 306 can be essentially free of burn. Burn may be evidence as portions of the side surfaces 321 and 323 having discoloration or having a residue or after etching having a whitish appearance indicating thermal damage to the surfaces during the finishing operation. The processes conducted according to the embodiments herein are capable of producing final surfaces exhibiting little to no burn.

The material removal operations conducted in accordance with embodiments herein may utilize a coolant provided at the interface of the grinding tool 301 and surface 321 or 323 of the slot 16. The coolant may be provided in a coherent jet as described in U.S. Pat. No. 6,669,118. In other embodiments, the coolant may be provided by flooding the interface area. The bonded abrasive bodies of the embodiments herein may facilitate use of a water-soluble coolant, which may be preferable for environmental reasons over certain other coolants (e.g. non water-soluble coolants). Other suitable coolants can include use of semi-synthetic and/or synthetic coolants. Still, it will be appreciated, that for certain operations, oil-based coolants can be used.

As further illustrated in FIG. 3 and according to one embodiment, during moving of the grinding tool 301 to conduct a material removal process, the grinding tool 301 can be tilted in a lateral plane relative to the workpiece 14. The lateral plane can be generally a plane defined by a major surface 331 of the workpiece 14. In certain instances, the lateral plane can be a plane generally perpendicular to the thickness of the workpiece, and may be a plane perpendicular to the portions of the pathways 310 and 311 along which the grinding tool 301 is contacting the workpiece 14. Moreover, the lateral axis 375 can extend within the lateral plane.

In particular instances, the grinding tool 301 can be tilted in the lateral plane relative to the workpiece 14 at a certain angle 309 defined as an angle between a normal axis 308 of the workpiece 14 in the lateral plane and an axis 307 of the grinding tool 301. The axis 307 of the grinding tool may

be an axis of the spindle, around which the grinding tool 301 is configured to rotate during the material removal operations. According to one embodiment, the angle 309 can be not greater than about 10 degrees, such as not greater than about 9 degrees, not greater than about 8 degrees, not greater than about 7 degrees, not greater than about 6 degrees, not greater than about 5 degrees, not greater than about 4 degrees, or even not greater than about 3 degrees. Still, in one non-limiting embodiment, the grinding tool 301 and workpiece 14 can be tilted relative to each other in the lateral plane at an angle 309 of at least about 0.1 degrees, at least about 0.3 degrees, at least about 0.6 degrees, at least about 0.8 degrees, at least about 1 degree, at least about 1.3 degrees, at least about 1.5 degrees, at least about 1.7 degrees, at least about 2 degrees, at least about 2.3 degrees, at least about 2.5 degrees. It will be appreciated that the angle 309 can be within a range between any value of the above minimum and maximum values.

In another aspect, during moving of the grinding tool 301 relative to the workpiece 14 to conduct a material removal operation, a bottom surface of the grinding tool 301 can be spaced apart from a bottom surface of the rough slot. FIG. 5 includes an illustration a process of moving a grinding tool to form a complex shape opening in a workpiece according to an embodiment. As illustrated, the grinding tool 301, and more particularly, the bonded abrasive body 303 can be in contact with at least a portion of a side surface 323 of the slot and a bottom surface 501 of the bonded abrasive body 303 can be spaced apart from a bottom surface 502 of the slot 16, which can facilitate formation of a lateral clearance gap 503 between the bottom surface 502 of the slot 16 and the bottom surface 501 of the bonded abrasive body 303. The lateral clearance gap 503 can be wedged shape, such that the clearance distance between the bottom surface 502 and bottom surface 501 can be lesser nearer the side surface 323 being contacted by the grinding tool 301 and greater farther away from the side surface 323 being contacted by the grinding tool 301. Moreover, during the material removal operation as illustrated, the bonded abrasive body 303 can be spaced away from the side surface 321 while removing material from the side surface 323.

According to one embodiment, the grinding tool 301 can be tilted at an angle sufficient to space the bottom surface 501 of the grinding tool 301 from the bottom surface 502 of the slot 16 (e.g., the rough slot 16 or a semi-finished slot). Accordingly, in one aspect, the process of removing material from at least a portion of one of the side surfaces of a slot 16 of the workpiece 14 can be conducted while simultaneously limiting contact of the bottom surface 501 of the grinding tool 301 and more particularly, the bonded abrasive body 303, with the bottom surface 502 of the slot 16. For certain material removal operations of the embodiments herein, a majority of a side surface of the bonded abrasive body 303 can be in contact with a majority of a side surface 323 of the slot 16 and a majority of a bottom surface 501 of the bonded abrasive body 303 can be spaced apart from a majority of the bottom surface 502 of the slot 16. It will be appreciated that all of the material removal processes of the embodiments herein, including the traversing of the grinding tool along

various pathways (e.g., a reciprocating pathway) can be conducted while the grinding tool 301 is maintained in a tilted configuration.

FIG. 6 includes an illustration of a process of moving a grinding tool to form a complex shape opening in a workpiece according to an embodiment. As illustrated, the grinding tool 301, and more particularly, the bonded abrasive body 303 can be in contact with at least a portion of the side surface 321 of the slot 16 opposite the side surface 323. Moreover, as provided in the illustration of the material removal process of FIG. 5, the bottom surface 501 of the bonded abrasive body 303 can be spaced apart from the bottom surface 502 of the slot 16, which can facilitate formation of a lateral clearance gap 543 between the bottom surface 502 of the slot 16 and the bottom surface 501 of the bonded abrasive body 303. As illustrated, the lateral clearance gap 543 distance between the bottom surface 502 and bottom surface 501 can be lesser nearer the side surface 321 being contacted by the grinding tool 301 and greater farther away from the side surface 321 being contacted by the grinding tool 301. According to one embodiment, the grinding tool 301 can be tilted at an angle sufficient to space the bottom surface 501 of the grinding tool 301 from the bottom surface 502 of the slot 16 (e.g., the rough slot 16 or a semi-finished slot). Moreover, during the material removal operation as illustrated, the bonded abrasive body 303 can be spaced away from the side surface 323 while removing material from the side surface 321.

FIG. 7A includes an illustration of a portion of a complex shape opening in a workpiece according to an embodiment. Notably, FIG. 7 includes an illustration of a portion of a complex shape opening 601 in a workpiece, wherein the bottom surface 502 of the workpiece 14 can be formed to have a substantially convex curvature 701. In at least one embodiment, the substantially convex curvature 701 can be defined as a portion of a raised portion 703 of the bottom surface 502. The raised portion 703 can have an upper surface defining the substantially convex curvature 701. Moreover, the raised portion 703 can extend vertically (or radially) into the complex shape opening 601. As illustrated, unlike an otherwise planar bottom surface 702, which is illustrated as a dotted line, the raised portion 703 can have a maximum height 704 that is at least about 0.01% of the total height 710 of the complex shape opening defined as the greatest distance in the vertical direction 377 between the bottom surface 502 of the complex shape opening 601 and a point on a line in the lateral direction 375 between points 751 and 752 defining the edge between the upper surface 754 of the workpiece 14 and the side surfaces 321 and 323 defining the complex shape opening 601, as illustrated in FIG. 7B. In other instances, the maximum height 704 can be a greater percentage of the total height 710, such as at least about 0.03%, at least about 0.05%, at least about 0.07%, at least about 0.09%, at least about 0.1%, at least about 0.13%, at least about 0.15%, at least about 0.17%, at least about 0.19%, at least about 0.2%, at least about 0.23%, at least about 0.25%, at least about 0.27%, at least about 0.29%, at least about 0.3%, at least about 0.4%, at least about 0.5%, at least about 0.7%, at least about 0.9%, or even at least about 1%. Still, in one embodiment, maximum

height 704 not greater than about 10%, such as not greater than about 9%, not greater than about 8%, not greater than about 7%, not greater than about 6%, not greater than about 5%, not greater than about 4%, or even not greater than about 3% of the total height 710. It will be appreciated that the calculation of the percentage of the maximum height (hm) 704 relative to the total height (ht) 710 can be based on the equation $[(ht-hm)/ht] \times 100\%$. Moreover, it will be appreciated that the maximum height can be within a range between any of the minimum and maximum percentages noted above.

In other embodiment, the raised portion 703 and more particularly, the substantially convex curvature 701 of the raised portion 703 of the bottom surface 502 can define at least a portion of a bottom surface 502 of the complex shape opening 601. Moreover, in other embodiment, the substantially convex curvature 701 can extend for at least a majority of the width in the lateral direction 375 of the bottom surface 502. In more particular instances, the substantially convex curvature 701 can extend for essentially the entire width in the lateral direction of the bottom surface 502.

FIG. 4 includes a cross-sectional illustration of an abrasive tool in accordance with an embodiment. In particular, the abrasive tool can be a mounted point abrasive tool which is configured to be rotated at high speeds for finishing of surfaces as described herein. Notable, the abrasive tool includes a bonded abrasive body incorporating abrasive particles dispersed throughout a volume and contained within a volume of bonding material as described herein. More particularly, as illustrated in FIG. 4, the bonded abrasive body can have a complex shape configured to finish complex shapes within a workpiece (e.g. re-entrant shapes).

In accordance with one embodiment, the bonded abrasive body 401 can have a longitudinal axis 450 extending along the length of the body 401 (i.e., the longest dimension of the body) between an upper surface 404 and a lower surface 403. Additionally, a lateral axis 451 can extend perpendicular to the longitudinal axis 450 and define the width of the body 401. In accordance with one embodiment, the complex shape of the bonded abrasive body 401 can be defined by a first radial flange 410 extending from the bonded abrasive body at a first axial position. For example, the first radial flange 410 can extend laterally along the lateral axis 451 and circumferentially around the body 401. The flange 410 can have a first surface 411 that extends radially from the body 401 at a first angle relative to the lateral axis 451. As illustrated, the intersection of the first surface 411 and the lateral axis 451 can define an acute angle 461. Likewise, the flange 410 can be further defined by a second surface 412 extending radially from the bonded abrasive body 410. The second surface 412 can be adjacent to, and even abutting, the first surface 411. The surface 412 can define an acute angle 462 between the lateral axis 451 and the surface 412.

Additionally, the bonded abrasive body 401 may be formed such that it includes a second radial flange 413, which may be distinct from the first radial flange 410. In fact, as illustrated in FIG. 4, the radial flange 413 can be spaced apart from the radial flange 410 along the longitudinal axis 450

at a second axial position, distinct from the axial position of the radial flange 410. In accordance with an embodiment, the radial flange 413 can be defined by surfaces 414 and 415 that can extend radially and circumferentially from the bonded abrasive body to define the flange 413.

In some instances, the cross-sectional shape of the bonded abrasive body 401 may be described as a single-flanged shape, double-flanged shape, triple-flanged shape, and the like. Such shapes can incorporate one or more radial flanges extending from the body to define a re-entrant shape. In other instances, it may be described as a re-entrant-shaped body such that it has dimensions suitable for finishing and forming of a re-entrant shape into a workpiece.

In accordance with one embodiment, the complex shape of the bonded abrasive body 401 may be described by a form depth (FD). The form depth can be described by the equation $[(Rl - Rs)/Rl]$, wherein R_s is a smallest radius (R_s) (i.e., half of the dimension 406) of the bonded abrasive body 401 at a point along the longitudinal axis 450 and R_l is a largest radius (R_l) (i.e., half of the dimension 408) of the bonded abrasive body 401 at a point along the longitudinal axis 450.

In one embodiment, the bonded abrasive body 401 has a form depth (FD) of at least about 0.1. In other embodiments, the bonded abrasive body 401 can have a form depth (FD) of at least about 0.15, at least about 0.2, at least about 0.3, at least about 0.4, at least about 0.5, at least about 0.6, at least about 0.7, or greater. Certain embodiments may utilize a bonded abrasive body 401 having a form depth (FD) within a range between about 0.3 and about 0.95, such as between about 0.4 and about 0.9, such as between about 0.5 and about 0.9.

The bonded abrasive body 401 may also be described by a form ratio (FR) described by the equation $[Fl/Fw]$. The dimension Fl is a form length measured as a dimension of the peripheral profile surface along a direction of the longitudinal axis 450 of the bonded abrasive body 401. In particular, the form length can describe the profile length of the bonded abrasive body 401 between points A and B illustrated on FIG. 4, defining the portion of the profile actively engaged in the material removal finishing process. The dimension Fw is a form width, which actually defines the length of the bonded abrasive body between the top surface 404 and the bottom surface 403 along a straight line of the longitudinal axis 450.

In accordance with one embodiment, the bonded abrasive body 401 can have a form ratio $[Fl/Fw]$ of at least about 1.1. In other instances, the bonded abrasive body 401 can have a form ratio of at least about 1.2, such as at least about 1.3, at least about 1.4, at least about 1.5, or even at least about 1.7. Particular embodiments may utilize a bonded abrasive body having a form ratio within a range between about 1.1 and about 3.0, such as between about 1.2 and about 2.8, such as between about 1.2 and about 2.5, such as between about 1.3 and about 2.2, or even between about 1.3 and about 2.0.

Certain dimensional aspects of the bonded abrasive body 401 may further be described by an overhang ratio. The overhang ratio of the bonded abrasive body 401 can be described by the equation

[OL/Dm], wherein Dm is a minimum diameter 406 at a point along the longitudinal axis 450 of the bonded abrasive body and OL is the length 407 between the bottom surface 403 of the bonded abrasive body 401 and the point along the longitudinal axis of the bonded abrasive body defining the minimum diameter 406.

According to certain embodiments, the bonded abrasive body 401 can have an overhang ratio (OR) of at least about 1.3. In still other instances, the bonded abrasive body 401 may be formed such that it has an overhang ratio of at least about 1.4, such as at least about 1.5, or even at least about 1.6. The overhang ratio for bonded abrasive body 401 can be within a range between about 1.3 and about 2.5, such as between about 1.3 and about 2.2.

In addition to the characteristics described herein, the bonded abrasive tools can be dressed in-situ with the finishing process. Dressing is understood in the art as a method of sharpening and reshaping of a bonded abrasive body, and is typically an operation conducted on bonded abrasive articles and not an operation suitable for use with other abrasive articles, including for example, single-layered abrasive tools (e.g. electroplated abrasive bodies).

The abrasive tool and method of finishing workpieces using the abrasive tools of embodiments herein represent a departure from the state of the art. In particular, state of the art mechanisms for finishing such workpieces and materials, particularly to form re-entrant shapes in materials to tight dimensional tolerances have not utilized the tools or mechanisms described herein. In particular, the abrasive tools of embodiments herein utilize a combination of features including, for example, abrasive particles disbursed volumetrically in a matrix of bonding material, complex shapes described by form depth, overhang ratio, and form ratio. Moreover, the bonded abrasive tools of embodiments herein are utilized in a particular manner to facilitate finishing operations having characteristics which have not been utilized before. In particular, the bonded abrasive tools are capable of finishing workpieces to complex re-entrant shapes under particular conditions including locational speeds of the tool, feed rates, material removal rates, finishing power, and the like. Moreover, utilization of the abrasive tools herein in combination with the methods described facilitates a new process for finishing of workpieces to tight dimensional tolerances while maintaining the shape of the tool thereby facilitating accuracy of the shape and surface formed and extending the usable life of the tool thereby improving the efficiency of the operation.

As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having,” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of features is not necessarily limited only to those features but may include other features not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive-or and not to an exclusive-or. For example, a condition A or B is satisfied by any one of

the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

The use of “a” or “an” is employed to describe elements and components described herein. This is done merely for convenience and to give a general sense of the scope of the invention. This description should be read to include one or at least one and the singular also includes the plural, or vice versa, unless it is clear that it is meant otherwise.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The materials, methods, and examples are illustrative only and not intended to be limiting. To the extent not described herein, many details regarding specific materials and processing acts are conventional and may be found in textbooks and other sources within the scintillation and radiation detection arts.

The above-disclosed subject matter is to be considered illustrative, and not restrictive, and the appended claims are intended to cover all such modifications, enhancements, and other embodiments, which fall within the true scope of the present invention. Thus, to the maximum extent allowed by law, the scope of the present invention is to be determined by the broadest permissible interpretation of the following claims and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

The Abstract of the Disclosure is provided to comply with Patent Law and is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing Detailed Description of the Drawings, various features may be grouped together or described in a single embodiment for the purpose of streamlining the disclosure. This disclosure is not to be interpreted as reflecting an intention that the claimed embodiments require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter may be directed to less than all features of any of the disclosed embodiments. Thus, the following claims are incorporated into the Detailed Description of the Drawings, with each claim standing on its own as defining separately claimed subject matter.

Item 1. A method of forming a complex form in a workpiece comprising: moving a grinding tool having a complex shape relative to a surface of a workpiece to form a complex shape opening in the workpiece, wherein the grinding tool is tilted in a lateral plane relative to the workpiece.

Item 2. A method of forming a complex form in a workpiece comprising: moving a grinding tool having a complex shape relative to a side surface of a rough slot in a workpiece to form at least a portion of a complex shape opening in a first side of the rough slot, wherein during moving, a bottom surface of the grinding tool is spaced apart from a bottom surface of the rough slot.

Item 3. A method of forming a complex form in a workpiece comprising: moving a grinding tool having a complex shape relative to a surface of a workpiece to form a complex shape opening in

the workpiece, wherein the grinding tool is tilted in a lateral plane relative to the workpiece, and wherein a bottom surface of the workpiece is formed to have a substantially convex curvature.

Item 4. The method of any one of items 1 and 3, further comprising forming a rough slot in the workpiece.

5 Item 5. The method of any one of items 2 and 4, further comprising forming a rough slot in the workpiece prior to moving the grinding tool.

Item 6. The method of any one of items 2 and 4, wherein forming a rough slot comprises rotating a grinding wheel having a generally annular shape against a portion of the workpiece to form the rough slot.

10 Item 7. The method of any one of items 2 and 4, wherein the rough slot comprises a simple shape, wherein the rough slot comprises a non-complex shape, wherein the rough slot comprises a generally rectangular cross-sectional shape as viewed in a lateral plane of the workpiece.

Item 8. The method of any one of items 1 and 2, wherein a bottom surface of the workpiece is formed to have a substantially convex curvature.

15 Item 9. The method of any one of items 3 and 8, wherein the substantially convex curvature defines at least a portion of the bottom surface having a raised portion.

Item 10. The method of any one of items 3 and 8, wherein the substantially convex curvature defines at least a portion of a bottom surface of the complex shape opening.

20 Item 11. The method of any one of items 1, 2, and 3, wherein the grinding tool comprises a grinding quill tool.

Item 12. The method of any one of items 2 and 3, wherein during moving, the grinding tool is tilted in a lateral plane relative to the workpiece.

Item 13. The method of any one of items 1 and 12, wherein the grinding tool is tilted at an angle sufficient to space a bottom surface of the grinding tool from a bottom surface of the workpiece.

25 Item 14. The method of any one of items 1 and 12, wherein the grinding tool is tilted at an angle relative to a normal axis of the workpiece in the lateral plane.

Item 15. The method of any one of items 1 and 12, wherein the grinding tool is tilted at an angle of not greater than about 10 degrees, not greater than about 9 degrees, not greater than about 8 degrees, not greater than about 7 degrees, not greater than about 6 degrees, not greater than about 5
30 degrees, not greater than about 4 degrees, not greater than about 3 degrees.

Item 16. The method of any one of items 1 and 12, wherein the grinding tool is tilted at an angle of at least about 0.1 degrees, at least about 0.3 degrees, at least about 0.6 degrees, at least about 0.8 degrees, at least about 1 degree, at least about 1.3 degrees, at least about 1.5 degrees, at least about 1.7 degrees, at least about 2 degrees, at least about 2.3 degrees, at least about 2.5 degrees.

Item 17. The method of any one of items 1 and 3, wherein the grinding tool is tilted at an angle sufficient to space a bottom surface of the grinding tool from a bottom surface of a rough slot in the workpiece.

5 Item 18. The method of any one of items 1, 2, and 3, wherein moving comprises removing material from at least a portion of a side surface of a rough slot of the workpiece while simultaneously limiting contact of a bottom surface of the grinding tool with a bottom surface of the rough slot.

Item 19. The method of any one of items 1, 2, and 3, wherein moving comprises rotating the grinding tool relative to the workpiece for forming a re-entrant shape opening in the workpiece.

10 Item 20. The method of any one of items 1, 2, and 3, wherein moving comprises finishing at least a portion of a surface of the workpiece defining a complex shape opening to a surface roughness (Ra) of not greater than about 2 microns.

Item 21. The method of any one of items 1, 2, and 3, wherein the workpiece comprises a metal or metal alloy, wherein the workpiece comprises a nickel-based superalloy material.

15 Item 22. The method of any one of items 1, 2, and 3, wherein moving comprises rotating the grinding tool at a speed of at least about 10,000 rpm and not greater than about 250,000 rpm.

Item 23. The method of any one of items 1, 2, and 3, wherein moving further comprises: contacting the grinding tool to at least a first portion of a first side surface of the workpiece on a first pass; and contacting the grinding tool to at least a second portion of a second side surface of the workpiece on a second pass, wherein the first portion and the second portion are different portions.

20 Item 24. The method of item 23, wherein the first side surface and the second side surface define different surfaces of the workpiece.

Item 25. The method of item 23, wherein the first surface defines a first side surface of a rough slot within the workpiece and the second surface defines a second side surface of a rough slot formed in the workpiece.

25 Item 26. The method of item 25, wherein after the first pass, the first side surface has a complex contour defining a portion of a complex shape opening.

Item 27. The method of item 25, wherein after the second pass, the second side surface has a complex contour defining a portion of a complex shape opening.

30 Item 28. The method of item 25, wherein the first side surface and second side surface are separated from each other by a bottom surface of the rough slot.

Item 29. The method of any one of items 1, 2, and 3, wherein moving further comprises: contacting the grinding tool to at least a first portion of a first side surface of the the workpiece on a first pass; and contacting the grinding tool to at least a second portion of a second side surface of the workpiece on a second pass, wherein the first side surface and the second side surface are different
35 surfaces separated from each other by a bottom surface.

Item 30. The method of any one of items 1, 2, and 3, wherein moving further comprises: contacting the grinding tool to at least a first portion of the workpiece on a first pass; and contacting the grinding tool to the first portion on a second pass, wherein the grinding tool is moved in different directions on the first pass and the second pass.

5 Item 31. The method of item 30, wherein the first pass includes removing material to a depth of not greater than about 100 microns from the surface.

Item 32. The method of any one of items 1, 2, and 3, wherein moving includes a moving the grinding tool at a feed rate of at least about 30 ipm [762 mm/min] and not greater than about 300 ipm [7620 mm/min].

10 Item 33. The method of any one of items 1, 2, and 3, wherein moving includes operating at a material removal rate of at least about 0.01 inches³/min/inch [0.11 mm³/sec/mm] and not greater than about 5 inches³/min/inch [22 mm³/sec/mm].

Item 34. The method of any one of items 1, 2, and 3, wherein moving includes operating at a power of not greater than about 5 Hp [3.75 kW] at a feed rate of the within a range between about 30
15 ipm [762 mm/min] and about 300 ipm [7620 mm/min].

Item 35. The method of any one of items 1, 2, and 3, wherein after moving, the workpiece is essentially free of burn.

Item 36. The method of any one of items 1, 2, and 3, wherein moving further includes providing a coolant, wherein the coolant comprises a water-soluble coolant, wherein the coolant is
20 provided at an interface between the grinding tool and the workpiece during moving, wherein the coolant includes oil coolant.

Item 37. The method of any one of items 1, 2, and 3, wherein the grinding tool comprises a body having a form depth (FD) of at least about 0.1, wherein the form depth is described by the equation $[(R_l - R_s)/R_l]$, wherein R_s is a smallest radius (R_s) at a point along the longitudinal axis of the
25 bonded abrasive body and R_l is a largest radius (R_l) at a point along the longitudinal axis of the bonded abrasive body, wherein the form depth (FD) is within a range between about 0.3 and about 0.95.

Item 38. The method of any one of items 1, 2, and 3, wherein the grinding tool comprises a complex shape comprising a first radial flange extending from a body of the grinding tool at a first
30 axial position.

Item 39. The method of any one of items 1, 2, and 3, wherein the grinding tool comprises a substantially planar bottom surface.

Item 40. The method of any one of items 1, 2, and 3, wherein the complex shape comprises a double-flanged shape.

35 Item 41. The method of any one of items 1, 2, and 3, wherein the complex shape of the grinding tool comprises a body including a form ratio (FR) of at least about 1.1 described by the

equation Fl/Fw , wherein Fl is a form length measured as a dimension of the peripheral profile surface along a direction of the longitudinal axis of the body, and Fw is a form width measured as a dimension of the body along the longitudinal axis between a top surface and a bottom surface, wherein the body comprises a form ratio (FR) within a range between about 1.1 and about 3.0.

5 Item 42. The method of any one of items 1, 2, and 3, wherein the complex shape of the grinding tool comprises a body including an overhang ratio (OR) of at least about 1.3, wherein the overhang ratio is described by the equation $[OL/Dm]$, wherein Dm is a minimum diameter at a point along the longitudinal axis of the body and OL is the length of a portion of the body between a bottom surface and the point along the longitudinal axis of the body defining the minimum diameter.

10 Item 43. The method of any one of items 1, 2, and 3, wherein the grinding tool comprises a bonded abrasive body having having abrasive particles contained within a bonding material.

 Item 44. The method of item 43, wherein the bonding material comprises a material selected from the group of materials consisting of organic, inorganic, and a combination thereof.

15 Item 45. The method of item 43, wherein the bonding material comprises an organic material selected from the group consisting of resins, epoxies, and a combination thereof.

 Item 46. The method of item 43, wherein the bonding material comprises an inorganic material selected from the group consisting of metals, metal alloys, ceramics, glasses, and a combination thereof.

20 Item 47. The method of item 43, wherein the bonding material comprises a ceramic material comprising a vitreous material.

 Item 48. The method of item 47, wherein the vitreous material comprises an oxide.

 Item 49. The method of item 43, wherein the abrasive particles comprise a superabrasive material.

25 Item 50. The method of item 43, wherein the abrasive particles consist essentially of diamond.

 Item 51. The method of item 43, wherein the abrasive particles consist essentially of cubic boron nitride (cBN).

30 Item 52. The method of item 43, wherein the abrasive particles have an average particle size of not greater than about 150 microns, not greater than about 125 microns, not greater than about 100 microns, wherein the abrasive particles have an average particle size within a range between about 10 microns and about 150 microns.

 Item 53. The method of item 43, wherein the abrasive particles comprise between about 2 vol% and about 60 vol% of the total volume of a body of the grinding tool.

35 Item 54. The method of item 43, wherein the bonding material comprises a vitreous material, and wherein the bonding material comprises between about 2 vol% and about 60 vol% of a total volume of a body of the grinding tool.

Item 55. The method of item 43, wherein the grinding tool comprises body including an amount of porosity within a range between about 0.5 vol% and about 60 vol% of the total volume of the body

WHAT IS CLAIMED IS:

1. A method of forming a complex form in a workpiece comprising:
moving a grinding tool having a complex shape relative to a surface of a workpiece to
form a complex shape opening in the workpiece, wherein the grinding tool is
tilted in a lateral plane relative to the workpiece.

2. A method of forming a complex form in a workpiece comprising:
moving a grinding tool having a complex shape relative to a side surface of a rough
slot in a workpiece to form at least a portion of a complex shape opening in a
first side of the rough slot, wherein during moving, a bottom surface of the
grinding tool is spaced apart from a bottom surface of the rough slot.

3. A method of forming a complex form in a workpiece comprising:
moving a grinding tool having a complex shape relative to a surface of a workpiece to
form a complex shape opening in the workpiece, wherein the grinding tool is
tilted in a lateral plane relative to the workpiece, and wherein a bottom surface
of the workpiece is formed to have a substantially convex curvature.

4. The method of any one of claims 1 and 3, further comprising forming a rough slot
in the workpiece.

5. The method of any one of claims 2 and 4, further comprising forming a rough slot
in the workpiece prior to moving the grinding tool.

6. The method of any one of claims 2 and 4, wherein forming a rough slot comprises
rotating a grinding wheel having a generally annular shape against a portion of the workpiece
to form the rough slot.

7. The method of any one of claims 2 and 4, wherein the rough slot comprises a
generally rectangular cross-sectional shape as viewed in a lateral plane of the workpiece.

8. The method of any one of claims 1 and 2, wherein a bottom surface of the
workpiece is formed to have a substantially convex curvature.

9. The method of any one of claims 3 and 8, wherein the substantially convex
curvature defines at least a portion of the bottom surface having a raised portion.

10. The method of any one of claims 3 and 8, wherein the substantially convex
curvature defines at least a portion of a bottom surface of the complex shape opening.

11. The method of any one of claims 1, 2, and 3, wherein the grinding tool comprises
a grinding quill tool.

12. The method of any one of claims 2 and 3, wherein during moving, the grinding tool is tilted in a lateral plane relative to the workpiece.

13. The method of any one of claims 1 and 12, wherein the grinding tool is tilted at an angle sufficient to space a bottom surface of the grinding tool from a bottom surface of the workpiece.

14. The method of any one of claims 1 and 12, wherein the grinding tool is tilted at an angle relative to a normal axis of the workpiece in the lateral plane.

15. The method of any one of claims 1 and 12, wherein the grinding tool is tilted at an angle of not greater than about 10 degrees.