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(54) **Title**: END MILL HAVING AN ASYMMETRIC INDEX ANGLE ARRANGEMENT FOR MACHINING TITANIUM
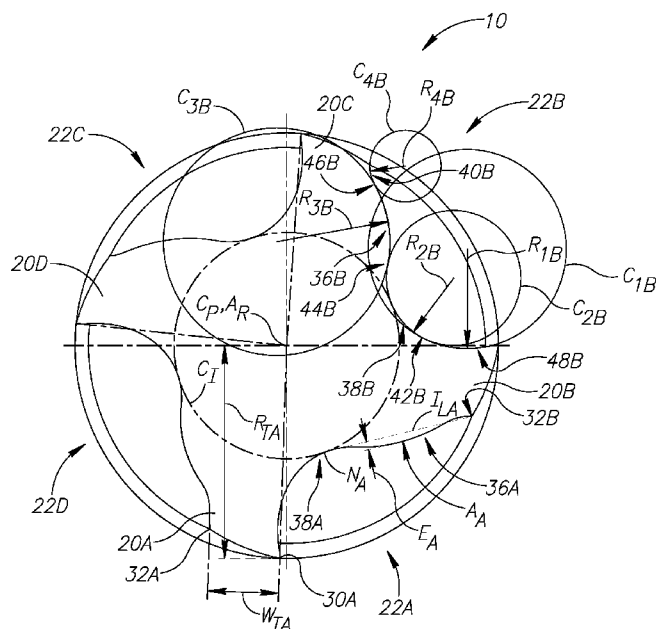
FIG.2C

(57) **Abstract**: An end mill (10) for machining titanium in-
cludes a cutting portion (14) having blunt teeth alternated
with flutes (22). Each flute (22) includes, in order from the
cutting edge (30), a rake surface (28), a concavely shaped
bending portion (38), a convexly shaped ejecting portion
(36) and a tooth relief edge (32). The convexly shaped
ejecting portion (36) has an ejection height E, which is
measurable between an apex of the ejecting portion (36) to
an imaginary straight line extending from a nadir of the ad-
jacent bending portion (36) of the flute (22) to the adjacent
tooth relief edge (32). In a plane perpendicular to a rotation
axis (AR) of the end mill (10), the ejection height E and a
cutting portion diameter D_E, fulfill the condition 0.01 OD_E
< E < 0.031 D_E.

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END MILL HAVING AN ASYMMETRIC INDEX ANGLE ARRANGEMENT FOR MACHINING TITANIUM

FIELD OF THE INVENTION

[001]   The subject matter of the present application relates to end mills configured for machining titanium.

BACKGROUND OF THE INVENTION

[002]   Titanium can be considered a relatively difficult material to mill as the properties thereof can quickly degrade an end mill. Such degradation is believed, in theory, to be at least in part due to heat transfer of a workpiece made of titanium to an end mill machining the workpiece.

[003]   Aside from heat transfer, another consideration when designing end mills is evacuation of chips. Flute shape is accordingly taken into account during end mill design. CN 20145538, CN 102303158 and CN 202199817 disclose end mills having flutes shape in accordance with different mathematical models.

[004]   Yet another consideration is reduction of end mill chatter. Reduction of chatter can be achieved, in theory, by designing end mills with asymmetric features, for example, as disclosed in US 6,991,409, US 7,306,408 and US 8,007,209. Fig. 1 of US 8,007,209 also discloses an end mill having serrations (Fig. 1, reference numeral 7).

[005]   While many end mills appear similar, upon close inspection there are often many small but relevant differences, some differences being critical as to whether an end mill can achieve a desired machining operation of a particular type of material or under particular cutting conditions.

[006]   Commonly, cutting edges are placed at different index angles with respect to each other, helix, radial rake and axial rake angles may vary at different cutting edges and even may vary along a single cutting edge. Orientation, position and size of each element in an end mill may have significant effect on the performance thereof.

[007]   In view of the extremely large number of variations of design possible, there is ongoing research to try and find more efficient end mills, especially for machining specific materials such as titanium.

[008]   It is an object of the present invention to provide a new and improved end mill.

SUMMARY OF THE INVENTION

[009]   It has been found that an end mill combining a particular tooth shape and a particular flute shape can achieve surprising longevity when machining titanium under certain conditions.

[0010]   More precisely, the tooth shape comprises a blunt cutting edge (the cutting edge being at an intersection of a rake cutting sub-surface and a relief surface) and a recessed rake sub-surface (hereinafter a "rake recessed sub-surface") extending from the rake cutting sub-surface.

[0011]   While blunt cutting edges could be considered detrimental, due to relatively increased machining power requirements caused thereby, experimental results have shown otherwise.

[0012]   More precisely, a blunt cutting edge is defined as having an actual internal cutting angle formed at an intersection of a rake cutting sub-surface and a relief surface, the actual internal cutting angle having a greater value than an imaginary internal cutting angle formed at an intersection of imaginary extension lines of the rake recessed sub-surface and the relief surface.

[0013]   It will be understood that use of the term "blunt" when referring to a cutting edge hereinafter is interchangeable with the definition above.

[0014]   Provision of a rake recessed sub-surface adjacent a rake cutting sub-surface (i.e. the rake recessed sub-surface adjacent being recessed further into a tooth than an adjacent rake cutting sub-surface relative to an imaginary radial line passing through the cutting edge, or, stated differently, the rake cutting sub-surface being raised above the rake recessed sub-surface relative to an imaginary radial line passing through the cutting edge), is believed, in theory, to reduce heat transfer to an end mill when machining titanium.

[0015]   Similarly, minimizing the length of a rake cutting sub-surface is also believed to reduce heat transfer by reducing contact of chips with an end mill rake surface.

[0016]   Referring now to the above-mentioned flute shape, the flute comprises a concavely shaped bending portion followed by a convexly shaped ejecting portion of a particular size.

[0017]   The bending portion is configured for bending titanium chips during a milling operation. A flute comprising a bending portion is illustrated in Fig. 4 of CN 102303158.

[0018]   Generally speaking, convexly shaped flute portions can provide structural strength to a tooth (i.e. allowing increased thickness thereof) and increased moment of inertia. The presence of such convex portion, however, reduces a flute's cross-sectional shape which is believed to be detrimental to chip evacuation from the flute. A flute without such convex portion is illustrated in Fig. 3 of CN 102303158.

[0019] It has now been found that provision of a convex portion, albeit of a specific size, can provide an advantageous chip ejection effect during machining of a titanium workpiece (consequently, the convexly shaped portion of the subject matter of the present application is entitled an "ejecting portion"). More precisely, it has been found that such ejecting portions provide better machining performance during titanium slotting operations which have limited space for chip evacuation, with particularly good results shown at relatively high titanium machining speeds.

[0020] A further consideration when machining titanium is reduction of chatter, typically by asymmetric features of an end mill. An end mill having an asymmetric index angle arrangement was found to have comparative longevity.

[0021] For the purposes of the specification and the claims, an end mill with a symmetric index angle arrangement is defined as one where, at a cutting end face, every flute has an index angle value identical to an index angle value of an opposing flute. Conversely, an end mill with an asymmetric index angle arrangement is one which does not fall within this definition.

[0022] In accordance with a first aspect of the subject matter of the present application, there is provided an end mill for machining titanium, the end mill comprising a cutting portion having teeth alternated with helically shaped flutes and a cutting portion diameter D_E; each tooth comprising a blunt cutting edge formed at an intersection of a rake cutting sub-surface and a relief surface, and a rake recessed sub-surface recessed in the tooth more than the rake cutting sub-surface; each flute comprising, in a plane perpendicular to a rotation axis of the end mill, a concavely shaped bending portion connected to a convexly shaped ejecting portion, the convexly shaped ejection portion having an ejection height E fulfilling the condition $0.010D_E < E < 0.031D_E$.

[0023] In accordance with another aspect of the subject matter of the present application, there is provided an end mill for machining titanium, having a longitudinally extending rotation axis A_R and comprising: a shank portion, and a cutting portion extending from the shank portion to a cutting end face and being integrally formed with at least four cutting teeth alternated with helically shaped flutes and having a cutting portion diameter D_E; each tooth comprising a rake surface, a relief surface, a cutting edge formed at an intersection of the rake and relief surfaces, and a relief edge spaced apart from the cutting edge and formed at an intersection of the relief surface and an adjacent surface of the flute succeeding the tooth; each rake surface comprising a

rake recessed sub-surface, a rake cutting sub-surface positioned further than the rake recessed sub-surface from the rotation axis and raised above the rake recessed sub-surface, relative to an imaginary radial line passing through the cutting edge, and a rake discontinuity formed at an intersection of the rake recessed and rake cutting sub-surfaces; wherein each tooth comprises an

5   actual internal cutting angle formed at an intersection of the rake cutting sub-surface and the relief surface, the actual internal cutting angle having a greater value than an imaginary internal cutting angle formed at an intersection of imaginary extension lines of the rake recessed sub-surface and the relief surface; wherein, in a plane perpendicular to the rotation axis A_R, each flute comprises a convexly shaped ejecting portion and a concavely shaped bending portion

10   connecting the ejecting portion and the rake recessed sub-surface; wherein the ejecting portion has an ejection height E which is measurable between an apex of the ejecting portion to an imaginary straight line extending from a nadir of the adjacent bending portion to the adjacent relief edge, the ejection height E having a magnitude fulfilling the condition $0.010D_E < E < 0.031D_E$; and wherein, at the cutting end face, index angles of the flutes are in an asymmetric

15   index angle arrangement.

[0024] In accordance with still another aspect of the subject matter of the present application, there is provided an end mill for machining titanium, having a longitudinally extending rotation axis A_R and comprising: a shank portion, and a cutting portion extending from the shank portion to a cutting end face and being integrally formed with at least four cutting teeth alternated with

20   helically shaped flutes and having a cutting portion diameter D_E; each tooth comprising a rake surface, a relief surface, a cutting edge formed at an intersection of the rake and relief surfaces, and a relief edge spaced apart from the cutting edge and formed at an intersection of the relief surface and an adjacent surface of the flute succeeding the tooth; each rake surface comprising a rake recessed sub-surface, a rake cutting sub-surface positioned further than the rake recessed

25   sub-surface from the rotation axis and raised above the rake recessed sub-surface, relative to an imaginary radial line passing through the cutting edge, and a rake discontinuity formed at an intersection of the rake recessed and rake cutting sub-surfaces; wherein each tooth comprises an actual internal cutting angle formed at an intersection of the rake cutting sub-surface and the relief surface, the actual internal cutting angle having a greater value than an imaginary internal

30   cutting angle formed at an intersection of imaginary extension lines of the rake recessed sub-surface and the relief surface; wherein each tooth has a rake cutting sub-surface length dimension

L_C, measured from the rake discontinuity thereof to the cutting edge thereof, fulfilling the condition $0.01R_T < L_C < 0.05R_T$, wherein R_T is the tooth's radius dimension, measured in a straight line from the rotation axis to the cutting edge; wherein each tooth has a radial rake angle within a range of 6° to -6°; wherein each flute has a helix angle H which fulfills the condition 30° < H < 50°; wherein, in a plane perpendicular to the rotation axis A_R, each flute comprises a convexly shaped ejecting portion and a concavely shaped bending portion connecting the ejecting portion and the rake recessed sub-surface; wherein the ejecting portion has an ejection height E which is measurable between an apex of the ejecting portion to an imaginary straight line extending from a nadir of the adjacent bending portion to the adjacent relief edge, the ejection height E having a magnitude fulfilling the condition $0.010D_E < E < 0.031D_E$; and wherein, at the cutting end face, index angles of the flutes are in an asymmetric index angle arrangement.

[0025] It will be understood that the above-said is a summary, and that any of the aspects above may further comprise any of the features described hereinbelow. Specifically, the following features, either alone or in combination, may be applicable to any of the above aspects:

A.   An ejection height E can have a magnitude which fulfills the condition $0.014D_E < E < 0.029D_E$. To elaborate, the range $0.010D_E < E < 0.031D_E$ is believed to be feasible for machining titanium, whereas the range $0.014D_E < E < 0.029D_E$ has achieved good results during testing. In theory, such moderate ejection height (i.e. $0.010D_E < E < 0.031D_E$) can facilitate a suitable tooth strength (by allowing a suitable tooth width) and moment of inertia.

B.   In each plane, of an effective cutting portion of an end mill, perpendicular to a rotation axis A_R, an ejecting portion and bending portion can be present. In each plane, the ejecting portion can have an ejection height E fulfilling the above mentioned conditions (i.e., $0.010D_E < E < 0.031D_E$, or $0.014D_E < E < 0.029D_E$).

C.   At least one helix angle can be different from another helix angle.

D.   A helix angle and an ejecting portion radius of one of the flutes can be smaller than a respective helix angle and an ejecting portion radius of another one of the flutes.

E.   Helix angles which are closer to a largest helix angle among the flutes than to a smallest helix angle among the flutes can be considered as relatively large helix angles and helix angles which are closer to a smallest helix angle than to the largest helix angle among the flutes can be considered as relatively small helix angles. Each flute with a relatively large helix angle can

have an ejecting portion radius larger than an ejecting portion of each flute with a relatively small helix angle.

F.   A helix angle and a bending portion radius of one of the flutes can be smaller than a respective helix angle and a bending portion radius of another one of the flutes.

G.   Helix angles which are closer to a largest helix angle among the flutes than to a smallest helix angle among the flutes can be considered as relatively large helix angles and helix angles which are closer to a smallest helix angle than to the largest helix angle among the flutes can be considered as relatively small helix angles. Each flute with a relatively large helix angle can have a bending portion radius larger than a bending portion of each flute with a relatively small helix angle.

H.   A bending portion radius of one of the flutes can be smaller than an ejecting portion radius thereof. Each flute's bending portion radius can be smaller than that flute's ejecting portion radius.

I.   Potentially beneficial arrangements of thickening portions for end mills with an asymmetric index angle arrangement can be as follows. At a cutting end face, each flute can comprise a concavely shaped thickening portion connecting an ejecting portion and relief edge thereof. Such thickening portions can increase tooth width and hence structural strength needed for machining titanium. One of the thickening portions can extend along only a portion of the cutting portion from the cutting end face. Each thickening portion other than the one thickening portion which extends along only a portion of the cutting portion, can extend along the entire cutting portion.

J.   At a cutting portion, a core diameter D_C can fulfill the condition $0.47D_E < D_C < 0.60D_E$. The core diameter D_C can be $0.53D_E \pm 0.01D_E$. The prior condition ($0.47D_E < D_C < 0.60D_E$) is believed to provide a feasible balance between flute size, for chip evacuation, and acceptable moment of inertia which can provide acceptable results for machining titanium. In theory, a value closer to $0.53D_E$ is believed to be optimal and such value has indeed achieved good results during testing.

K.   An actual internal cutting angle can have a value which differs from the imaginary internal cutting angle by 4° to 15°. The actual internal cutting angle can differ from the imaginary internal cutting angle by 8° to 13°. The prior condition (4° to 15°) is believed to be

feasible for machining titanium. In theory, reducing the difference (in particular to 8° to 13°) is believed to be optimal and the latter range has indeed achieved good results during testing.

L.   Radial rake angles of each tooth can be within a range of 6° to -6°. Radial rake angles can be 2° ± 1° and -2° ± 1°. The prior range (6° to -6°) is believed to be feasible for machining

5   titanium. In theory, smaller angles (i.e. utilizing radial rake angles smaller than 6° and -6°) is believed to increase machining performance of titanium. Indeed, values of about 2° and about -2° achieved good results during testing.

M.   Teeth of an end mill can be in an arrangement wherein each second radial rake angle has the same value, which value differs from the radial rake angle of the alternate teeth.

10   N.   Each tooth can have a rake cutting sub-surface length dimension L_C, measured from a rake discontinuity to a cutting edge of the same tooth, fulfilling the condition $0.01R_T < L_C < 0.05R_T$, wherein R_T is the tooth's radius dimension measured in a straight line from the rotation axis to the cutting edge. A rake cutting sub-surface length dimension L_C can be $0.026R_T \pm 0.005R_T$. The prior range ($0.01R_T < L_C < 0.05R_T$) is believed to be feasible for machining

15   titanium. In theory, a cutting sub-surface length dimension L_C value closer to $0.026R_T$ is believed to be optimal and such value has indeed achieved good results during testing.

O.   At a cutting end face, index angles of the flutes can be in an asymmetric index angle arrangement. Index angles of the flutes can be in an asymmetric index angle arrangement along the entire length of the cutting portion.

20   P.   All of the index angles at the cutting end face can be different. Index angles at each cross-section of the cutting portion can be different.

Q.   In an end view, an end mill can comprise relatively longer teeth and relatively shorter teeth. The longer teeth can be skewed relative to each other (i.e. non-parallel).

R.   All tooth widths at the cutting end face can have the same magnitude. Such arrangement

25   facilitates production.

S.   For end mills with index angles in an asymmetric index angle arrangement it has been found beneficial to vary tooth widths. More precisely, tooth widths can vary at positions spaced apart from the cutting end face. Such arrangement can, in certain circumstances, provide structural strength. Good results were achieved in an arrangement where every second tooth

30   width increases in width and every alternate tooth width decreases in width.

T.   At the cutting end face, each tooth can have a tooth width W_T fulfilling the condition $0.13D_E < W_T < 0.22D_E$. At the cutting end face, a tooth width W_T can be $0.165D_E \pm 0.01D_E$. The prior range ($0.13D_E < W_T < 0.22D_E$) is believed to be feasible for machining titanium. In theory, a tooth width W_T value closer to $0.165D_E$ is believed to be optimal and such value has indeed achieved good results during testing.

U.   Each associated rake cutting sub-surface and rake recessed sub-surface can be arranged relative to one another such that a chip cut from a workpiece contacts the rake cutting sub-surface, but not the rake recessed sub-surface immediately adjacent the rake discontinuity on a side away from the cutting edge.

V.   Each tooth can be free of serrations.

W.   An end mill can have a tool life of at least 60 minutes while machining titanium, specifically TI6AL4V, at a speed V_C of 80.0 meters per minute, a feed rate F_Z of 0.08 millimeters per tooth, a chip thickness a_e of 2.00 millimeters, a depth a_p of 22.0 millimeters. Under such machining conditions the tool life can be at least 80 minutes or at least 90 minutes.

X.   Each flute can have a helix angle H which fulfills the condition $30° < H < 50°$. A helix angle H can be $35° \pm 1°$ or $37° \pm 1°$. The prior range is believed to be feasible for machining titanium. In theory, the values closer to $35°$ and $37°$ are believed to be optimal, and such values indeed achieved good results during testing. The helix angles can each be constant or variable (i.e. changing in value at one or more points, or changing in value at each point along a length of the cutting portion) along the length of the flute.

Y.   Each rake recessed sub-surface can be concavely shaped. Each rake recessed sub-surface can have an identical shape.

Z.   Each flute can be shaped to allow single-pass production thereof (allowing simpler manufacture than multi-pass production).

BRIEF DESCRIPTION OF THE DRAWINGS

[0026]   For a better understanding of the subject matter of the present application, and to show how the same may be carried out in practice, reference will now be made to the accompanying drawings, in which:

Fig. 1A is a perspective view of an end mill in accordance with the subject matter of the present application;

Fig. 1B is a side view of the end mill in Fig. 1A;

Fig. 2A is an end view of the end mill in Figs. 1A and 1B;

Fig. 2B is a cross-section view taken along line 2B-2B in Fig. 1B;

Fig. 2C is an enlarged view of Fig. 2B with imaginary circles added;

Figs. 3A and 3B are enlarged views of cutting edges shown in Fig. 2B; and

Figs. 4A-4E show test results of end mills including the end mill in Figs. 1A-3B.

DETAILED DESCRIPTION

[0027] Reference is made to Figs. 1A and 1B, which illustrate an end mill 10, typically made of extremely hard and wear-resistant material such as cemented carbide, configured for machining titanium and for rotating about a rotation axis A_R extending longitudinally through the center thereof. In this example the end mill 10 rotation direction D_R is counter-clockwise in the view shown in Fig. 2A.

[0028] The end mill 10 comprises a shank portion 12 and a cutting portion 14 extending therefrom.

[0029] The cutting portion 14 has a cutting portion diameter D_E and extends along the rotation axis A_R in a rearward axial direction D_B from a cutting end face 16 to a furthermost flute end 18.

[0030] The cutting portion 14 is integrally formed with first, second, third and fourth teeth 20A, 20B, 20C, 20D, alternated with first, second, third and fourth helically shaped flutes 22A, 22B, 22C, 22D.

[0031] Referring also to Fig. 2A, the index angles I_A, I_B, I_C, I_D are in an asymmetric index angle arrangement. The index angles can each have different values, with the following pattern: $I_A = 92°$, $I_B = 86°$, $I_C = 88°$, $I_D = 94°$, at the cutting end face 16, having been found effective.

[0032] Also, as shown in Fig. 2A, are first and third teeth 20A, 20C which are shorter than the second and fourth teeth 20B, 20D, with the latter pair being skewed relative to each other.

[0033] Hereinbelow, similar elements initially differentiated with alphabetic suffixes (e.g., "20A", "20B") may subsequently be referred to in the specification and claims without such suffixes (e.g., "20"), when referring to common features.

[0034] Referring also to Fig. 2B, each tooth 20 comprises a relief surface 26A, 26B, 26C, 26D a rake surface 28A, 28B, 28C, 28D, a cutting edge 30A, 30B, 30C, 30D formed at intersections of the relief and rake surfaces 26, 28 and a relief edge 32A, 32B, 32C, 32D formed at

intersections of each relief surface 26 and an adjacent surface 40 of a succeeding flute 22. In this example, at the cutting end face 16, a thickening portion 40, described further below, is the closest (adjacent) portion of each succeeding flute 22 and, therefore, for example, the first relief edge 32A, at the cutting end face 16, is formed at an intersection of the first relief surface 26A and the fourth thickening portion's surface 40D.

[0035]   The cutting portion 14 has an effective cutting length L extending from the cutting end face 16 to a cutting length plane P_C extending perpendicular to the rotation axis A_R and positioned where the flutes 22 begin to exit (i.e. become more shallow) or where tooth relief surfaces 33 are no longer effective.   An effective cutting portion is defined from the cutting end face 16 to the cutting length plane P_C.

[0036]   The end mill 10 can be gashed, and in this example end gashes 34 are shown in Fig. 2A.

[0037]   Each flute 22 comprises a convexly shaped ejecting portion 36A, 36B, 36C, 36D, a concavely shaped bending portion 38A, 38B, 38C, 38D connecting each ejecting portion 36 and each rake surface 28.

[0038]   Each flute 22 can also comprise a corresponding one of first, second, third and fourth concavely shaped thickening portions 40A, 40B, 40C, 40D connecting an associated ejecting portion 36 and relief edge 32 thereof.

[0039]   As shown in Figs. 1A and 1B, a thickening portion, specifically the thickening portion designated 40B, extends along only partially along the cutting portion 14. Conversely, the remaining thickening portions 40A, 40C, 40D can extend along the entire cutting portion 14. The lack of a thickening portion 40B along a portion of the cutting portion 14 can be limited to only one of the multiple teeth 20. Such arrangement can assist in providing tooth strength.

[0040]   Referring now to Fig. 2C, each ejecting portion 36, bending portion 38 and rake recessed sub-surface 48 (described in further detail hereinafter) can be curved and can have a radius R corresponding to a portion of an imaginary circle C. For simplicity, the following description relates to the second flute 22B only, yet corresponding elements and reference characters are understood to be present for each flute 22 of this example. More precisely: the second rake recessed sub-surface 48B can have a rake radius R_{1B} corresponding to the radius of an imaginary rake circle C_{1B}; the second bending portion 38B can have a bending radius R_{2B} corresponding to the radius of imaginary bending circle C_{2B}; the second ejecting portion 36B can have an ejecting radius R_{3B} corresponding to the radius of imaginary ejecting circle C_{3B}; and the

second thickening portion 40B can have a thickening radius R_{4B} corresponding to the radius of imaginary thickening circle C_{4B}. Within a flute's cross-section, changes from one curvature to another can occur at discontinuities therealong. For example: a first flute discontinuity 42B can be positioned at an intersection of the second rake recessed sub-surface 48B and the second bending portion 38B; a second flute discontinuity 44B can be positioned at an intersection of the second bending portion 38B and the second ejecting portion 36B; and a third flute discontinuity 46B can be positioned at an intersection of the second ejecting portion 36B and the second thickening portion 40B.

[0041]   It will be understood that actual end mill portions may deviate slightly from being perfectly circular. Accordingly, rake recessed sub-potions, bending portions, ejecting portions and thickening portions should be considered to approximately have such radii.

[0042]   Referring to the first flute 22A as an example, measurement of an ejection height E is exemplified as follows: the ejection height E_A is measurable between an apex A_A of the first ejecting portion 36A to an imaginary straight line I_{LA} extending from a nadir N_A of the adjacent bending portion 38A (i.e., the nadir N being a closest point of a bending portion to a center point C_P of an end mill) to the associated, adjacent second relief edge 32B (the second relief edge 32B defined for convenience as part of the associated second tooth 20B, however also being associated with the adjacent, succeeding first flute 22A).

[0043]   Each flute 22 has a helix angle H (Fig. 1B) formed with the rotation axis A_R. In this example, the helix angle H of first and third flutes 22A and 22C is 37° and the helix angle of second and fourth flutes 22B and 22D is 35°. The first and third flutes 22A and 22C having a helix angle H of 37° are considered to have large helix angles, relative to the second and fourth flutes 22B and 22D having a helix angle H of 35°.

[0044]   Exemplified feasible dimensions for different diameter examples are shown in the table below (with the dimensions relating to the 12mm example corresponding to the end mill 10 example described).

Cutting portion diameter D_E	Flutes	Rake radius R_1, as a percentage of D_E	Bending radius R_2, as a percentage of D_E	Ejecting radius R_3, as a percentage of D_E	Helix Angle H
6.35mm	22B, 22D	23.6	16	27	35.5
	22A, 22C	23.6	17	35	37
12mm	22B, 22D	25	16	27	35
	22A, 22C	25	17	40	37
19.05mm	22B, 22D	29	15	29	35
	22A, 22C	29	17	37	37

[0045]   As shown in Fig. 2B, the cutting portion 14 has a core diameter D_C. The core diameter D_C is defined as twice a sum of distances from the center point C_P to a closest point of each flute 22, divided by the number of flutes. In the present example the flutes all have equal depth and consequently the core diameter D_C is the diameter of an inscribed circle C_I shown in Fig. 2B. To elaborate, in examples where the flutes have unequal depth, the core diameter D_C is twice the average distance from the center point C_P to a closest point of each flute.

[0046]   Referring to Fig. 2C, each tooth 20, referring to the first tooth 20A as an example, has a tooth radius R_{TA} and a tooth width W_{TA}.

[0047]   In the example shown, each tooth radius R_T has the same magnitude. Consequently, the cutting portion diameter D_E is twice the magnitude of the tooth radius R_T. In examples where the teeth have unequal tooth radii, the cutting portion diameter D_E is defined as twice a sum of tooth radii R_T divided by the number of teeth.

[0048]   The tooth width W_{TA} is measurable between a first imaginary line extending from the center point C_P to the cutting edge 30A and a second imaginary line parallel with the first imaginary line and which intersects the relief edge 32A.

[0049]   In the example shown, each tooth width W_{TA} can have the same magnitude, at least at the cutting end face 16. For tooth strength, for end mills with index angles in an asymmetric arrangement, tooth widths have been found to be effective when varied at positions spaced apart from the cutting end face 16. In this example, the first and third teeth 20A, 20C decrease in width from the cutting end face 16 and the second and fourth teeth 20B, 20D increase in width from the cutting end face 16.

[0050]   For simplicity, the following description is made regarding two teeth 20B, 20C only. It is noted that in this example the geometry of tooth 20A is identical to tooth 20C, and the geometry of tooth 20B is identical to tooth 20D.

[0051]   Referring to Figs. 3A and 3B, the rake surfaces 28B, 28C each comprise a rake recessed sub-surface 48B, 48C a rake cutting sub-surface 50B, 50C and a rake discontinuity 52B, 52C formed at an intersection thereof.

[0052]   To simplify manufacture, the rake recessed sub-surfaces 48 can have the same shape, which can be a concave shape as shown in Figs. 3A and 3B. Notably, the shape is recessed from the associated rake cutting sub-surface 50 so that metal chips which have been cut from a workpiece (not shown) can preferably pass over the rake recessed sub-surfaces 48 without contact, especially at points immediately adjacent the rake discontinuity 52, thereby reducing heat transfer to the end mill.

[0053]   Each rake cutting sub-surface 50 has an actual internal cutting angle γ_B, γ_C having a greater value than an imaginary internal cutting angle λ_B, λ_C associated with the rake recessed sub-surface 48 of the same tooth 20. More precisely, referring to Fig. 3B as an example, an imaginary rake extension line 53B, extending the second rake recessed sub-surface 48B from the rake discontinuity 52B intersects an imaginary relief extension line 55B which extends the second relief surface 26B and forms an acute internal cutting angle λ_B at an intersection thereof.

[0054]   As best seen in Figs. 3A and 3B, the cross-section of each rake cutting sub-surface 50 can be straight.

[0055]   Each tooth 20 can have a rake cutting sub-surface length dimension L_C (shown only in Fig. 3A, but existing for each rake cutting sub-surface 50). In this example, L_C is $0.026R_T$.

[0056]   Each tooth 20 can have a radial rake angle β measured from an imaginary radial line L_R of the end mill 10 which extends from rotation axis A_R to the cutting edge 30, to the rake cutting sub-surface 50.

[0057]   In the example shown, the radial rake angle β_B of the second tooth 20B is -2° and the radial rake angle β_C of the third tooth 20C is 2°.

[0058]   The relief surfaces 26 can both form the same radial relief angle α_B, α_C, measured relative to an imaginary circular line L_{TB}, L_{TC} having the same diameter of the associated tooth 20. In the example shown, the radial relief angles α_B, α_C are 7°.

[0059]   Test results shown in Figs. 4A to 4E, show comparative tool lives of different end mills designed for machining titanium.   In each instance, tool life was determined by halting machining at predetermined intervals (or upon detecting a rise in power requirements for machining) and determining the wear of the tool. Tool failure, after which continued machining was halted, was considered to be upon flank wear reaching 0.2mm or corner wear reaching 0.5mm.

[0060]   In the tests end mills numbered as:

-        "no. 1" are in accordance with the subject matter of the present application;

-        "no. 2" are notably different from end mill no. 1, in that the cutting edges are not blunt, and they have a different coating, serrated teeth and common helix angles for the entire length of the cutting portion;

-        "no. 3" have the same coating as end mill no. 1, but notable differences include serrated teeth, the cutting edges not being blunt, and common helix angles for the entire length of the cutting portion;

-        "no. 4" have the same blunt cutting edges as end mill no. 1, but notable differences include a different coating, serrated teeth, and common helix angles;

-        "no. 5" have the same blunt cutting edges and coating as end mill no. 1, but notable differences include serrated teeth and common helix angles;

-        "no. 6" are the same as no. 2, except with a different substrate thereto;

-        "no. 7" have an ejecting portion in accordance with the subject matter of the present application and the same coating, but one notable difference to end mill no. 1 is a symmetric index angle arrangement; and

-        "no. 8" has the same coating as end mill no. 1, but a notable difference is that the cutting edges are not blunt.

[0061]   More particularly, Figs. 4A to 4E each show the results of testing the end mills by cutting a different metal under specific machining conditions.   Table 1 below shows the

correspondence between each of Figs. 4A to 4E, regarding the metal being cut and the machining conditions, and Table 2 presents, in tabular form, the test results.

	Fig. 4A	Fig. 4B	Fig. 4C	Fig. 4D	Fig. 4D
Tested Material	Titanium TI6AL4V	Titanium TI6AL4V	Steel AISI 4340 Hardness 42 (HRc)	Stainless Steel 304L Hardness 190 (HRb)	Steel DIN 1.2311 Hardness 52 (HRc)
speed V_C (meters/minute)	60.0	80.0	180.0	100.0	140.0
feed rate F_Z (mm per tooth)	0.08	0.08	0.08	0.08	0.04
chip thickness a_e (mm)	2.00	2.00	5.00	4.00	3.00
depth a_p (mm)	22.0	22.0	20.0	22.0	22.0

Table 1 - Tested Materials and Machining Conditions

End mill no.	Fig. 4A (minutes)	Fig. 4B (minutes)	Fig. 4C (minutes)	Fig. 4D (minutes)	Fig. 4E (minutes)
1	137.70, 76.50	91.80 (no tool failure)	48.00	40.00	10.00
2	45.90, 122.40, 76.50	15.30	36.00	Not tested	Not tested
3	107.10	15.30	Not tested	Not tested	25.00
4	122.40, 76.50	15.30	Not tested	Not tested	Not tested
5	91.80	15.30	Not tested	Not tested	Not tested
6	91.80	30.60	Not tested	Not tested	Not tested
7	Not tested	Not tested	Not tested	30.00	10.00
8	Not tested	Not tested	62.00	40.00	Not tested

Table 2 – Tool Life (time till halt) for end mills

[0062]   The results of the titanium machining test shown in Fig. 4B indicate that end mill no. 1, which was made in accordance with the subject matter of the present application, had a significantly longer tool life than the other end mills tested at a speed of 80.0 meters per minute, with and testing thereof being voluntarily halted as further machining was not deemed necessary.

[0063]   In view of the remarkable result, an additional verification test (not shown) was carried out on another titanium plate to confirm that the plate used in the test shown in Fig. 4B was not sub-standard.

[0064]   Notably, however, the results shown in Figs. 4C – 4E indicate that comparative longevity was not evident when machining other materials, and was not clearly shown at a lower machining speed in the results in Fig. 4A.

[0065]   The description above includes an exemplary embodiment which does not exclude non-exemplified embodiments from the claim scope of the present application.

CLAIMS

1. An end mill for machining titanium, having a longitudinally extending rotation axis A_R and comprising:

    a shank portion, and

    a cutting portion extending from the shank portion to a cutting end face and being integrally formed with at least four cutting teeth alternated with helically shaped flutes and having a cutting portion diameter D_E;

    each tooth comprising

    a rake surface,

    a relief surface,

    a cutting edge formed at an intersection of the rake and relief surfaces, and

    a relief edge spaced apart from the cutting edge and formed at an intersection of the relief surface and an adjacent surface of the flute succeeding the tooth

    each rake surface comprising

    a rake recessed sub-surface,

    a rake cutting sub-surface positioned further than the rake recessed sub-surface from the rotation axis and raised above the rake recessed sub-surface, relative to an imaginary radial line passing through the cutting edge, and

    a rake discontinuity formed at an intersection of the rake recessed and rake cutting sub-surfaces;

    wherein each tooth comprises an actual internal cutting angle formed at an intersection of the rake cutting sub-surface and the relief surface, the actual internal cutting angle having a greater value than an imaginary internal cutting angle formed at an intersection of imaginary extension lines of the rake recessed sub-surface and the relief surface;

wherein each tooth has a rake cutting sub-surface length dimension L_C measured from the rake discontinuity thereof to the cutting edge thereof, fulfilling the condition $0.01R_T < L_C < 0.05R_T$, wherein R_T is the tooth's radius dimension, measured in a straight line from the rotation axis to the cutting edge;

wherein each tooth has a radial rake angle within a range of 6° to -6°;

wherein each flute has a helix angle H which fulfills the condition $30° < H < 50°$;

wherein, in a plane perpendicular to the rotation axis A_R, each flute comprises a convexly shaped ejecting portion and a concavely shaped bending portion connecting the ejecting portion and the rake recessed sub-surface;

wherein the ejecting portion has an ejection height E which is measurable between an apex of the ejecting portion to an imaginary straight line extending from a nadir of the adjacent bending portion to the adjacent relief edge, the ejection height E having a magnitude fulfilling the condition $0.010D_E < E < 0.031D_E$; and

wherein, at the cutting end face, index angles of the flutes are in an asymmetric arrangement.

2. The end mill according to the previous claim, wherein the ejection height E has a magnitude which fulfills the condition $0.014D_E < E < 0.029D_E$.

3. The end mill according to claim 1 or 2, wherein said ejecting portion, bending portion and ejection height E, are present in each plane perpendicular to the rotation axis A_R of an effective cutting portion of the end mill.

4. The end mill according to any one of the previous claims, wherein a helix angle and an ejecting portion radius of one of the flutes is smaller than a respective helix angle and an ejecting portion radius of another one of the flutes.

5. The end mill according to the previous claim, wherein helix angles which are closer to a largest helix angle of the flutes than to a smallest helix angle of the flutes are considered as relatively large helix angles and helix angles which are closer to a smallest helix angle than to the largest helix angle of the flutes are considered as relatively small helix angles, and each flute with a relatively large helix angle has an ejecting portion radius larger than an ejecting portion radius of each flute with a relatively small helix angle.

6.   The end mill according to any one of the previous claims, wherein a helix angle and a bending portion radius of one of the flutes is smaller than a respective helix angle and a bending portion radius of another one of the flutes.

7.   The end mill according to the previous claim, wherein helix angles which are closer to a largest helix angle of the flutes than to a smallest helix angle of the flutes are considered as relatively large helix angles and helix angles which are closer to a smallest helix angle than to the largest helix angle of the flutes are considered as relatively small helix angles, and each flute with a relatively large helix angle has a bending portion radius larger than a bending portion radius of each flute with a relatively small helix angle.

8.   The end mill according to any one of the previous claims, wherein one of the flute's bending portion radius is smaller than an ejecting portion radius thereof or each flute's bending portion radius is smaller than each ejecting portion radius thereof.

9.   The end mill according to any one of the previous claims, wherein, at the cutting end face, each flute comprises a concavely shaped thickening portion connecting the ejecting portion and the relief edge.

10.   The end mill according to the previous claim, wherein one of the thickening portions extends along only a portion of the cutting portion or, except for said one thickening portion, each thickening portion extends along the entire cutting portion.

11.   The end mill according to any one of the previous claims, wherein at the cutting portion, a core diameter D_C fulfills the condition $0.47D_E < D_C < 0.60D_E$, or the core diameter D_C is $0.53D_E \pm 0.01D_E$.

12.   The end mill according to any one of the previous claims, wherein the actual internal cutting angle has a value which differs from the imaginary internal cutting angle by 4° to 15°, or which differs from the imaginary internal cutting angle by 8° to 13°.

13.   The end mill according to any one of the previous claims, wherein rake angles of the teeth are 2° ± 1° or -2° ± 1°.

14.   The end mill according to any one of the previous claims, wherein the teeth are in an arrangement wherein each second radial rake angle has the same value, which value differs from the radial rake angle of the alternate teeth.

15.   The end mill according to any one of the previous claims, wherein each tooth has a rake cutting sub-surface length dimension L_C, measured from the rake discontinuity to the cutting edge of the same tooth, fulfilling the condition $0.01R_T < L_C < 0.05R_T$, wherein R_T is the respective tooth's radius dimension or the rake cutting sub-surface length dimension L_C is $0.026R_T \pm 0.005R_T$.

16.   The end mill according to any one of the previous claims, wherein all of the index angles are different at: (i) the cutting end face, or (ii) at each cross-section of the cutting portion, or (iii) both.

17.   The end mill according to any one of the previous claims, wherein all tooth widths at the cutting end face are the same magnitude.

18.   The end mill according to any one of the previous claims, wherein tooth widths vary from one another, at positions spaced apart from the cutting end face.

19.   The end mill according to the previous claim, wherein every second tooth width grows in width and every alternate tooth width decreases in width.

20.   The end mill according to any one of the previous claims, wherein, in an end view, the end mill comprises relatively longer teeth and relatively shorter teeth, wherein the longer teeth are skewed relative to each other.

21.   The end mill according to any one of the previous claims, wherein each associated rake cutting sub-surface and rake recessed sub-surface are arranged relative to one another such that a chip cut from a workpiece contacts the rake cutting sub-surface, but not the rake recessed sub-surface immediately adjacent the rake discontinuity on a side away from the cutting edge.

22.   The end mill according to any one of the previous claims, wherein each tooth is free of serrations.

23.   The end mill according to any one of the previous claims, wherein index angles of the flutes are in an asymmetric arrangement along the entire length of the cutting portion.

24.   The end mill according to any one of the previous claims, wherein the end mill has a tool life of at least 60 minutes while machining titanium, specifically TI6AL4V, at a speed V_C

of 80.0 meters per minute, a feed rate F_Z of 0.08 millimeters per tooth, a chip thickness a_e of 2.00 millimeters, a depth a_p of 22.0 millimeters.

25. The end mill according to the previous claim, wherein the tool life is at least 80 minutes or at least 90 minutes.

26. The end mill according to any one of the previous claims, wherein helix angle H of the flutes are $35° \pm 1°$ or $37° \pm 1°$.

27. The end mill according to any one of the previous claims, wherein each tooth, at the cutting end face, can have a tooth width W_T fulfilling the condition $0.13D_E < W_T < 0.22D_E$, or $0.165D_E \pm 0.01D_E$.
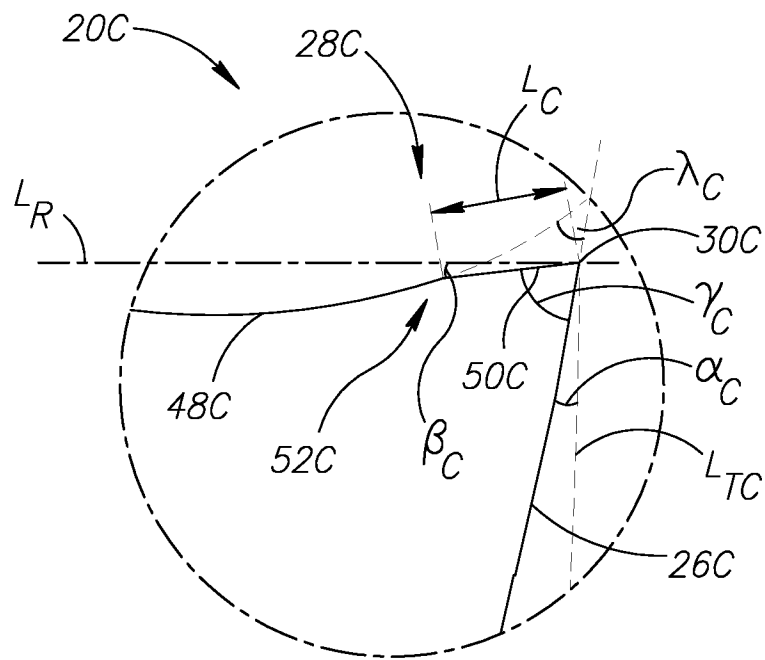
FIG.1A

FIG.1B

2/6
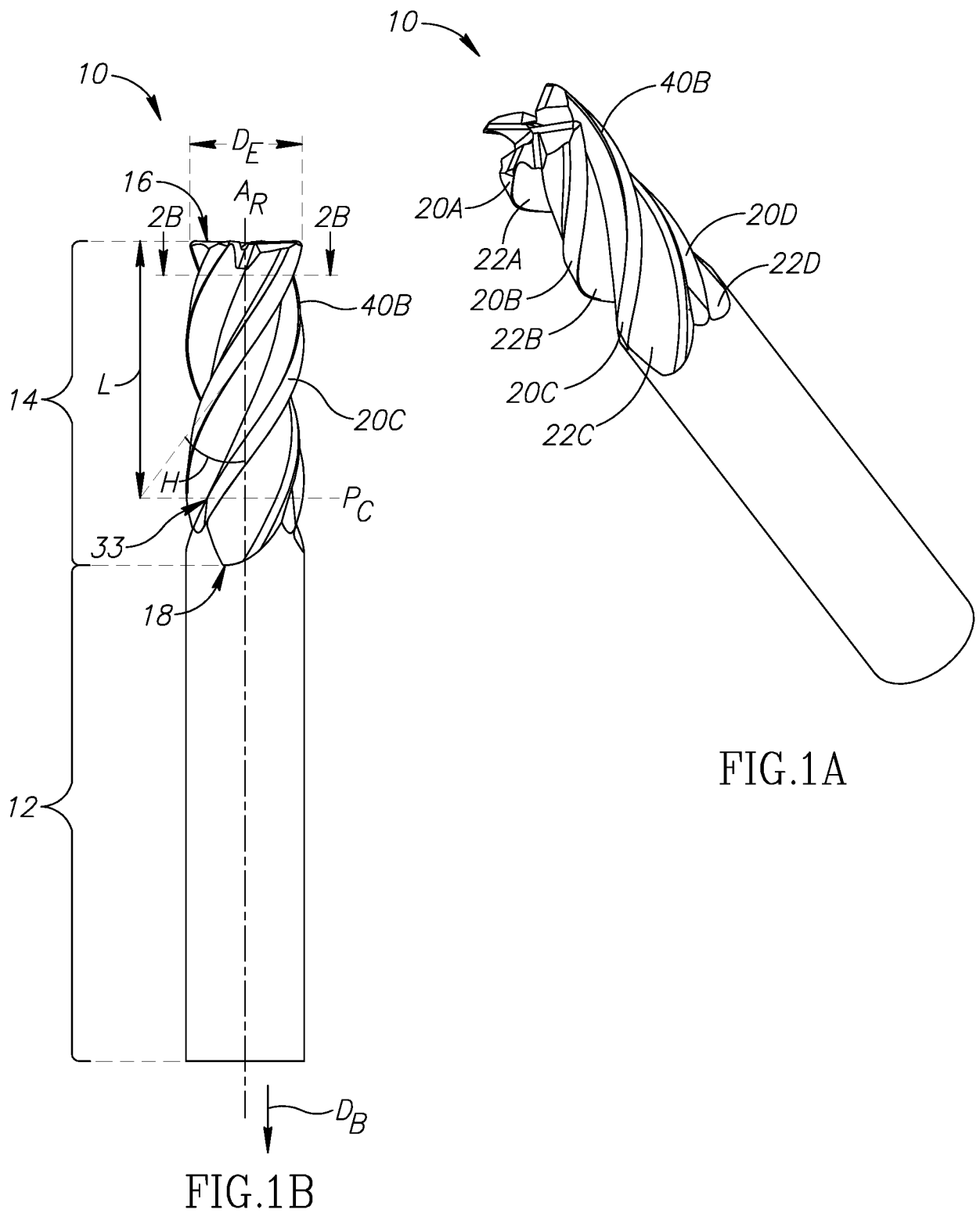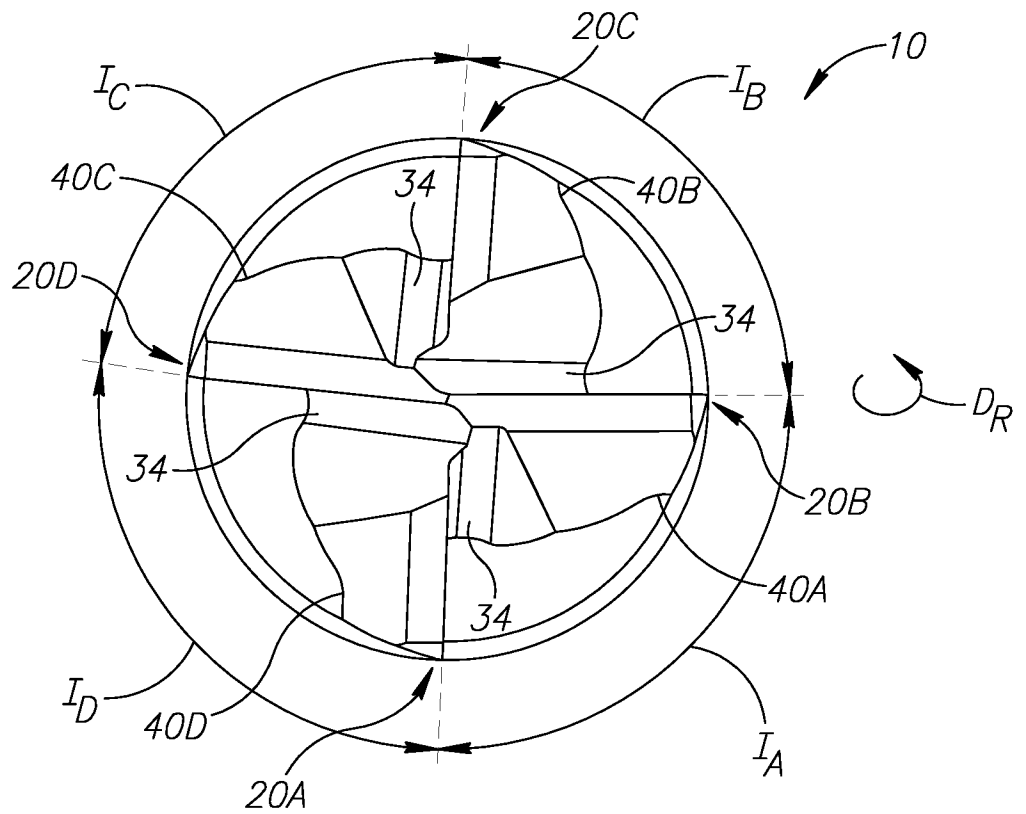
FIG.2A
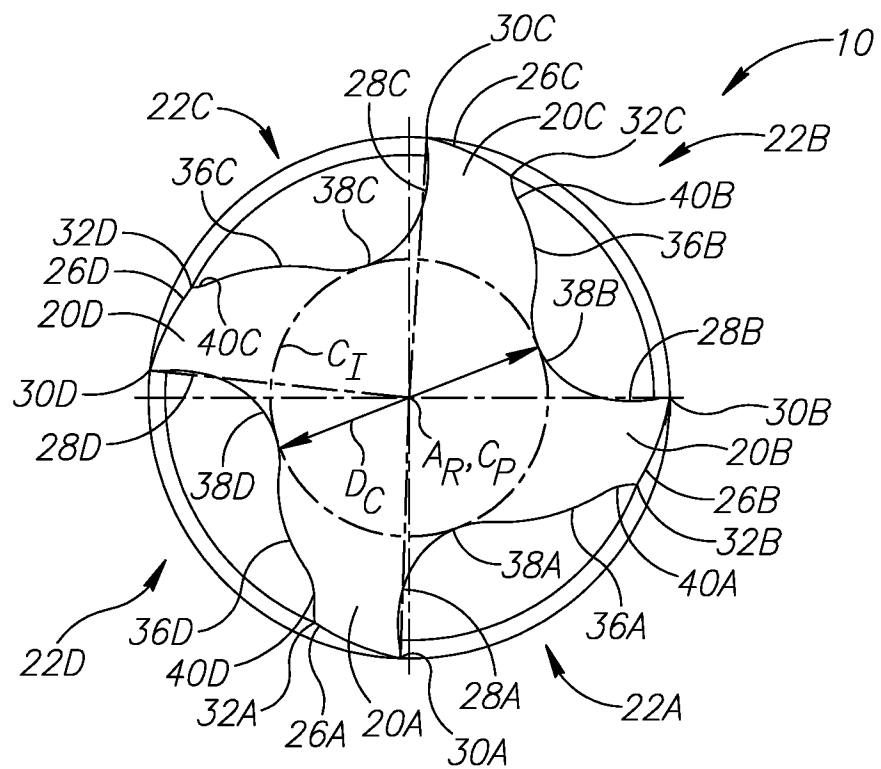
FIG.2B
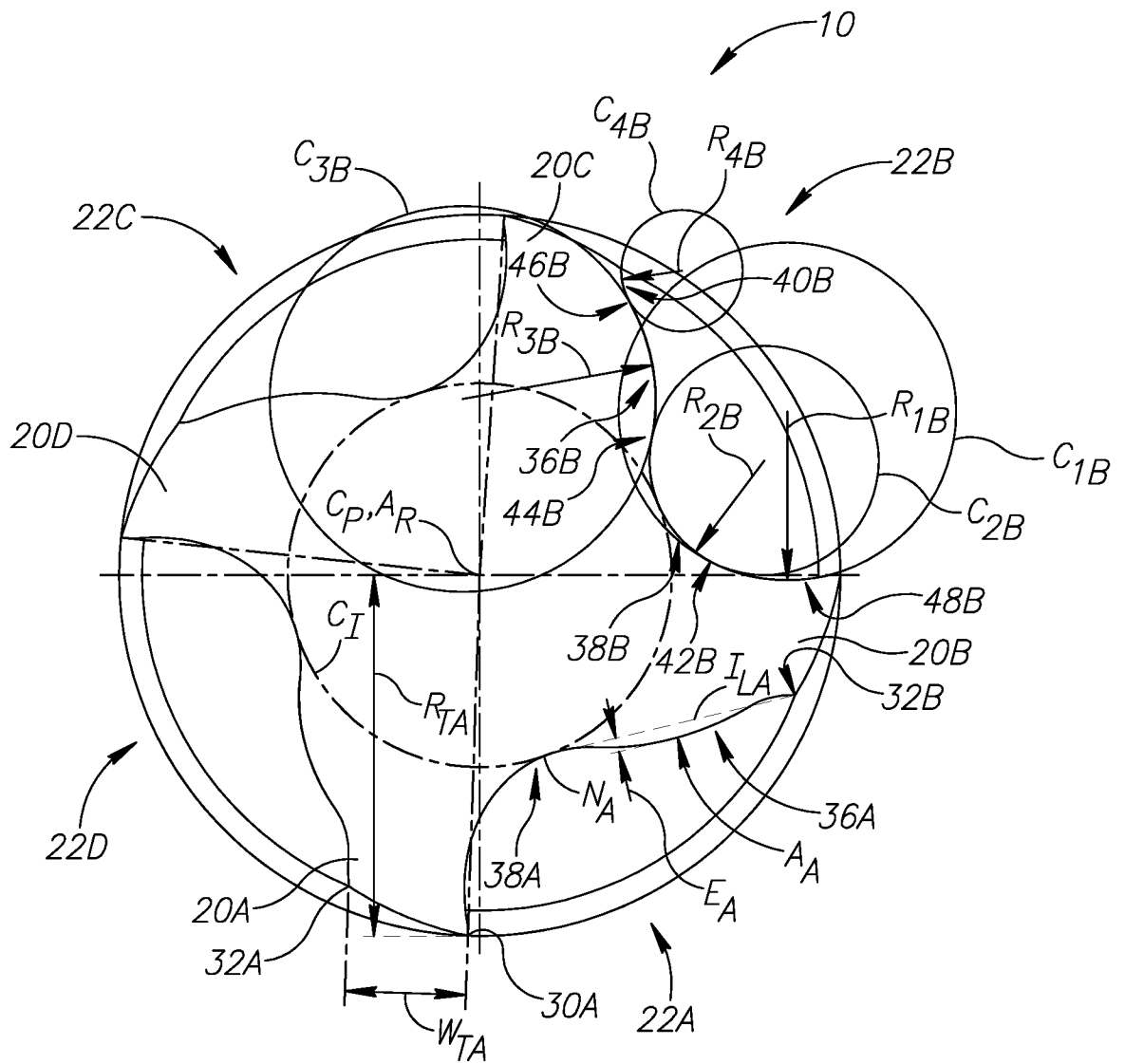
FIG.2C

FIG.3A

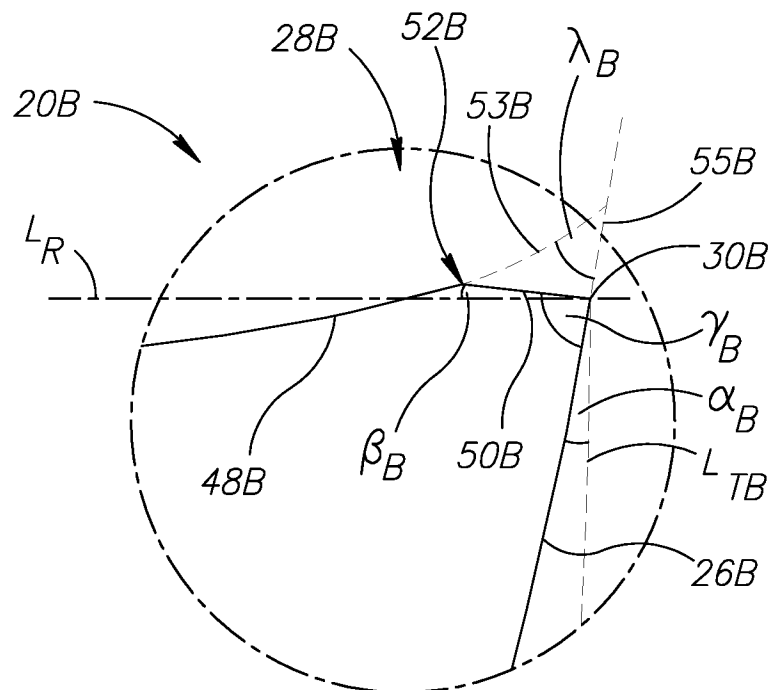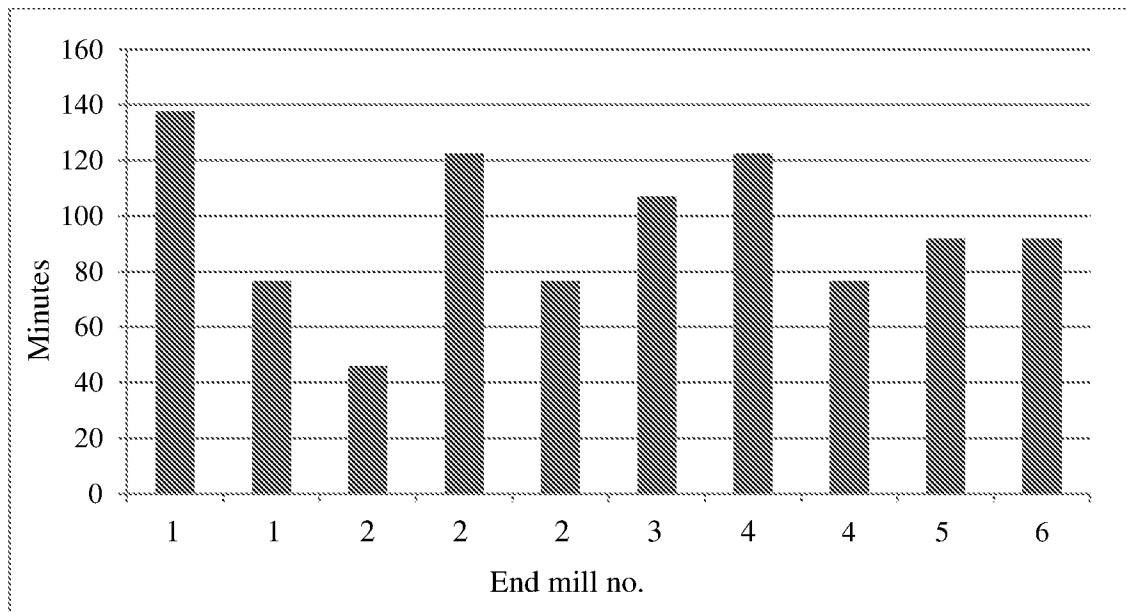FIG.3B

5/6

FIG.4A
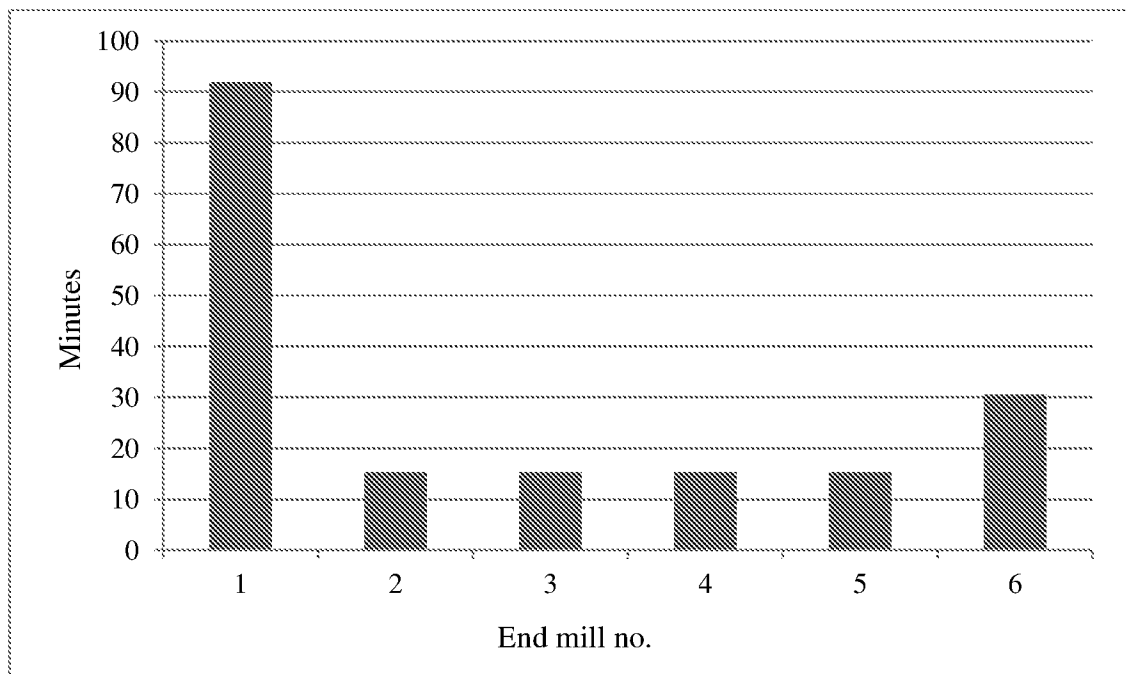
FIG.4B

6/6
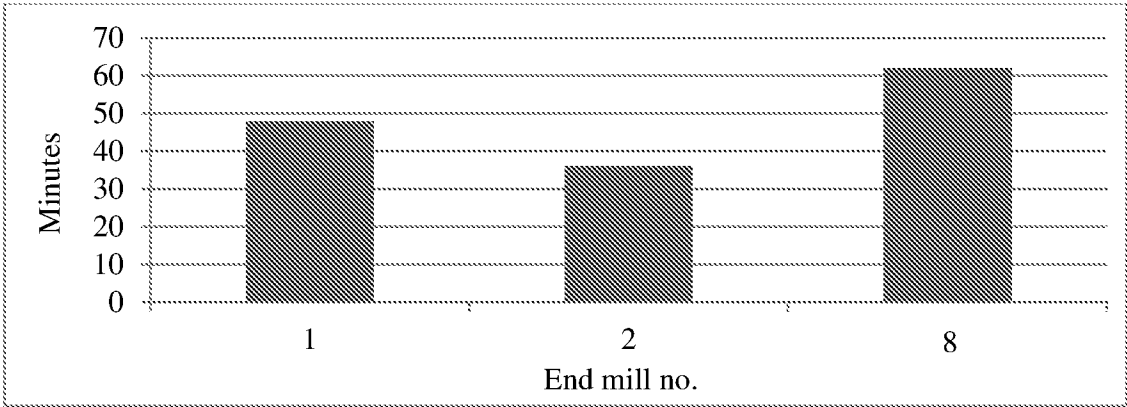
FIG.4C
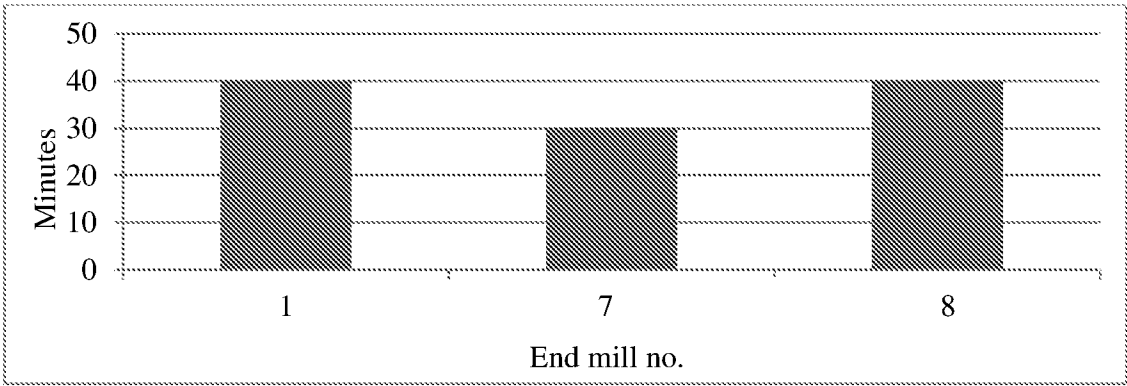
FIG.4D
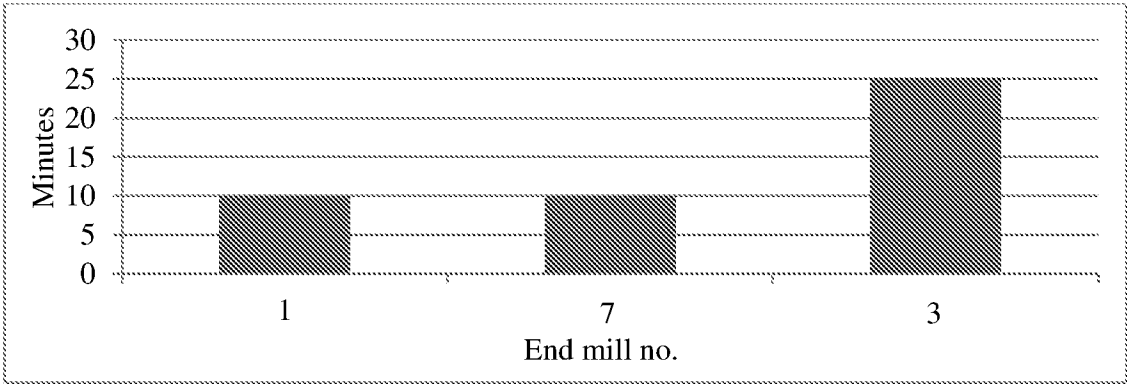
FIG.4E

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23C5/10
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B23C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2007/196186 A1 (VOLOKH VLADIMIR [IL]) 23 August 2007 (2007-08-23) paragraph [0029]; figure 4 ----- -/--	1,22

[X] Further documents are listed in the continuation of Box C.   [X] See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2014	11/06/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Barrow, Jeffrey

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A	JP 2005 297108 A (NAT AEROSPACE LAB) 27 October 2005 (2005-10-27) figure 4a -----	1
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C(Continuation).   DOCUMENTS CONSIDERED TO BE RELEVANT

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