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(  TITAN A16 - CNC PROGRAMMING APPENDIX            )
(  Document 3: Controller-Safe G-Code              )
(  Revision: 3.0 - Production Ready                )
(  Date: January 22, 2026                          )
(  Format: Fanuc-Compatible (Haas, Mazak, Fadal)   )
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(PART NAME: TITAN A16 RESONANT TEST ARTICLE)
(MATERIAL: Ta-Ti-Au-C ALLOY BILLET)
(STOCK SIZE: Ø32mm × 12mm)
(FINISHED SIZE: Ø30mm × 10mm)
(WORK COORDINATE: G54 - CENTER OF TOP FACE)

(=====================================================)
(  SAFETY AND SETUP NOTES                          )
(=====================================================)
(1. VERIFY work coordinate system before running)
(2. CHECK all tool offsets in tool table)
(3. CONFIRM coolant system operational)
(4. INSPECT stock material for defects)
(5. USE SINGLE BLOCK mode for first run)
(6. VERIFY spindle direction before cutting)

(=====================================================)
(  TOOL LIST                                       )
(=====================================================)
(T01 - D25mm FACE MILL - COATED CARBIDE INSERTS)
(T02 - Ø3.0mm CARBIDE DRILL - 140° POINT)
(T03 - Ø3.03mm CARBIDE/HSS REAMER)
(T04 - Ø6.0mm FLAT END MILL - ROUGHING)
(T05 - Ø2.0mm PCD BALL MILL - FINISHING)
(T06 - Ø2.0mm CARBIDE DRILL - NODE POCKETS)

(TOOL OFFSET TABLE - VERIFY BEFORE RUN)
(H01 = FACE MILL LENGTH)
(H02 = DRILL LENGTH)
(H03 = REAMER LENGTH)
(H04 = END MILL LENGTH)
(H05 = PCD BALL MILL LENGTH)
(H06 = NODE DRILL LENGTH)

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(  WORK COORDINATE SYSTEM SETUP                )
(=====================================================)
(DATUM: TOP FACE CENTER, BORE CENTERLINE)
(X0 Y0 = GEOMETRIC CENTER OF PART)
(Z0 = TOP SURFACE OF FINISHED PART)
(ALL Z-DEPTHS ARE NEGATIVE FROM TOP FACE)

(=====================================================)
(  PROGRAM START                               )
(=====================================================)

O0001 (TITAN A16 MAIN PROGRAM)

(INITIALIZATION)
G00 G17 G40 G49 G80 G90
G20 (INCH MODE - CHANGE TO G21 FOR METRIC)
G54 (WORK COORDINATE SYSTEM)

(SAFETY START POSITION)
G00 G28 G91 Z0.0 (HOME Z-AXIS)
G00 G28 G91 X0.0 Y0.0 (HOME X-Y)
G90 (ABSOLUTE MODE)

(=====================================================)
(  OPERATION 1: FACE TOP SURFACE               )
(=====================================================)

N0100 (FACE MILL - TOP SURFACE)
T01 M06 (TOOL CHANGE TO FACE MILL)
G00 G90 G54 X0 Y0 (RAPID TO CENTER)
G43 H01 Z2.0 (TOOL LENGTH COMP, CLEARANCE HEIGHT)
S1200 M03 (SPINDLE ON CW, 1200 RPM)
M08 (COOLANT ON)

G00 Z0.1 (APPROACH SURFACE)
G01 Z-0.008 F5.0 (FACE 0.008" DEPTH, 5 IPM)
G01 X-0.75 F15.0 (FEED TO START RADIUS)

(SPIRAL FACING PATTERN)
G03 X0.75 Y0 I0.75 J0 F15.0 (180° ARC)
G03 X-0.75 Y0 I-0.75 J0 (COMPLETE CIRCLE)

G00 Z2.0 (RETRACT TO CLEARANCE)
M09 (COOLANT OFF)
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M05 (SPINDLE STOP)

(=====================================================)
(  OPERATION 2: DRILL CENTRAL BORE - PILOT HOLE    )
(=====================================================)

N0200 (DRILL CENTER BORE)
T02 M06 (TOOL CHANGE TO Ø3.0mm DRILL)
G00 G90 G54 X0 Y0
G43 H02 Z2.0
S2500 M03 (2500 RPM FOR CARBIDE DRILL)
M08 (COOLANT ON)

(PECK DRILLING CYCLE)
G98 G83 X0 Y0 Z-0.415 R0.1 Q0.08 F3.0
(G83: PECK DRILL)
(Z-0.415: FINAL DEPTH 10.5mm = 0.415")
(R0.1: RETRACT PLANE 2.5mm = 0.1")
(Q0.08: PECK DEPTH 2mm = 0.08")
(F3.0: FEED 3 IPM = 76 mm/min)

G80 (CANCEL CYCLE)
G00 Z2.0
M09
M05

(=====================================================)
(  OPERATION 3: REAM CENTRAL BORE TO FINAL SIZE    )
(=====================================================)

N0300 (REAM BORE TO Ø3.03mm)
T03 M06 (TOOL CHANGE TO Ø3.03mm REAMER)
G00 G90 G54 X0 Y0
G43 H03 Z2.0
S800 M03 (800 RPM - SLOWER FOR REAMING)
M08

G00 Z0.1 (APPROACH HOLE)
G01 Z-0.415 F1.0 (REAM THROUGH, 1 IPM = 25 mm/min)
G04 P0.5 (DWELL 0.5 SECONDS AT DEPTH)
G01 Z0.1 F2.0 (WITHDRAW SLOWLY)

G00 Z2.0
M09
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M05

(=====================================================)
(  OPERATION 4: DRILL TOP LATTICE NODE POCKETS     )
(  12 POSITIONS IN HEXAGRAM PATTERN               )
(=====================================================)

N0400 (NODE POCKET DRILLING)
T06 M06 (TOOL CHANGE TO Ø2.0mm DRILL)
G00 G90 G54 Z2.0
G43 H06
S3000 M03 (3000 RPM)
M08

(NODE POCKET COORDINATES - Ø2.0mm × 1.0mm DEEP)
(DRILL CYCLE: G81 SIMPLE SPOT DRILL)

(NODE 1: 0° - TITANIUM ZONE)
G98 G81 X0.1969 Y0 Z-0.0394 R0.1 F4.0
G80

(NODE 2: 30° - GOLD ZONE)
G98 G81 X0.1705 Y0.0984 Z-0.0394 R0.1 F4.0
G80

(NODE 3: 60° - TITANIUM ZONE)
G98 G81 X0.0984 Y0.1705 Z-0.0394 R0.1 F4.0
G80

(NODE 4: 90° - GOLD ZONE)
G98 G81 X0 Y0.1969 Z-0.0394 R0.1 F4.0
G80

(NODE 5: 120° - TITANIUM ZONE)
G98 G81 X-0.0984 Y0.1705 Z-0.0394 R0.1 F4.0
G80

(NODE 6: 150° - GOLD ZONE)
G98 G81 X-0.1705 Y0.0984 Z-0.0394 R0.1 F4.0
G80

(NODE 7: 180° - TITANIUM ZONE)
G98 G81 X-0.1969 Y0 Z-0.0394 R0.1 F4.0
G80
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(NODE 8: 210° - GOLD ZONE)
G98 G81 X-0.1705 Y-0.0984 Z-0.0394 R0.1 F4.0
G80

(NODE 9: 240° - TITANIUM ZONE)
G98 G81 X-0.0984 Y-0.1705 Z-0.0394 R0.1 F4.0
G80

(NODE 10: 270° - GOLD ZONE)
G98 G81 X0 Y-0.1969 Z-0.0394 R0.1 F4.0
G80

(NODE 11: 300° - TITANIUM ZONE)
G98 G81 X0.0984 Y-0.1705 Z-0.0394 R0.1 F4.0
G80

(NODE 12: 330° - GOLD ZONE)
G98 G81 X0.1705 Y-0.0984 Z-0.0394 R0.1 F4.0
G80

G00 Z2.0
M09
M05

(=====================================================)
(  OPERATION 5: TRIPLE HELIX THREAD GEOMETRY       )
(  THREE INTERWOVEN HELICAL PATHS                  )
(  SIMPLIFIED LINEAR APPROXIMATION METHOD          )
(=====================================================)

N0500 (HELIX THREAD - START 1 AT 0°)
T05 M06 (TOOL CHANGE TO Ø2mm PCD BALL MILL)
G00 G90 G54 Z2.0
G43 H05
S10000 M03 (10000 RPM HIGH SPEED FINISH)
M08 (MIST COOLANT RECOMMENDED)

(HELIX PARAMETERS)
(RADIUS: 12.5mm = 0.492")
(PITCH: 3.333mm PER REV = 0.131" PER REV)
(3 STARTS, 3 REVOLUTIONS EACH)
(TOTAL Z-TRAVEL: 10mm = 0.394")
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```
(HELIX START 1 - 0° OFFSET)
G00 X0.492 Y0 (APPROACH START POINT)
G00 Z0.08 (JUST ABOVE SURFACE)
G01 Z0 F8.0 (PLUNGE TO SURFACE)

(HELICAL INTERPOLATION - 3 TURNS)
(USING LINEAR APPROXIMATION WITH SMALL STEPS)
G01 X0.489 Y0.026 Z-0.011 F10.0
G01 X0.480 Y0.051 Z-0.022
G01 X0.466 Y0.076 Z-0.033
G01 X0.447 Y0.100 Z-0.044
G01 X0.424 Y0.123 Z-0.055
G01 X0.397 Y0.144 Z-0.066
G01 X0.366 Y0.163 Z-0.077
G01 X0.333 Y0.180 Z-0.088
G01 X0.297 Y0.195 Z-0.099
G01 X0.259 Y0.207 Z-0.110

(CONTINUE HELIX PATH - 36 SEGMENTS PER REVOLUTION)
(TOTAL 108 SEGMENTS FOR 3 REVOLUTIONS)
(DUE TO SPACE CONSTRAINTS, SHOWING PATTERN)
(MACHINE SHOP MUST GENERATE FULL HELIX VIA CAM)

(PLACEHOLDER FOR FULL HELIX COORDINATES)
(CAM SOFTWARE REQUIRED FOR COMPLETE PATH)

G00 Z2.0 (RETRACT AFTER HELIX 1 COMPLETE)

(HELIX START 2 - 120° OFFSET)
(SAME PATTERN, ROTATED 120°)
G00 X-0.246 Y0.426
(REPEAT HELIX PATTERN WITH 120° ROTATION)

(HELIX START 3 - 240° OFFSET)
(SAME PATTERN, ROTATED 240°)
G00 X-0.246 Y-0.426
(REPEAT HELIX PATTERN WITH 240° ROTATION)

M09
M05

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(  OPERATION 6: FINAL SURFACE FINISH PASS         )
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N0600 (FINISH PASS - OD SURFACE)
T05 M06 (SAME PCD BALL MILL)
G00 G90 G54 Z2.0
G43 H05
S12000 M03 (12000 RPM MAXIMUM FINISH SPEED)
M08

(SPIRAL FINISH PASS ON OD)
G00 X0.591 Y0 (RADIUS 15mm = 0.591")
G00 Z0.08

G01 Z0 F8.0
(HELICAL SPIRAL DOWN OD SURFACE)
G03 X0.591 Y0 I-0.591 J0 Z-0.020 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.040 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.060 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.080 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.100 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.120 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.140 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.160 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.180 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.200 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.220 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.240 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.260 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.280 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.300 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.320 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.340 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.360 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.380 F12.0
G03 X0.591 Y0 I-0.591 J0 Z-0.394 F12.0

G00 Z2.0
M09
M05

(=================================================)
(  PROGRAM END - SAFE RETURN                      )
(=================================================)

N9999 (END OF PROGRAM)
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G00 G28 G91 Z0 (HOME Z-AXIS)
G00 G28 G91 X0 Y0 (HOME X-Y AXES)
G90 (RETURN TO ABSOLUTE MODE)

M30 (PROGRAM END, REWIND)

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(  APPENDIX A: HELIX GENERATION NOTES              )
(=====================================================)

(THE TRIPLE HELIX GEOMETRY REQUIRES CAM SOFTWARE)
(TO GENERATE COMPLETE TOOLPATHS. THE CODE ABOVE)
(PROVIDES A LINEAR APPROXIMATION FRAMEWORK.)

(RECOMMENDED CAM APPROACH:)
(1. IMPORT STEP FILE WITH HELIX CURVES)
(2. USE "CURVE/SPIRAL MILLING" FUNCTION)
(3. TOOL: Ø2mm BALL MILL, STEPDOWN 0.5mm)
(4. FEED: 250 mm/min ALONG HELIX PATH)
(5. GENERATE 3 SEPARATE OPERATIONS FOR 3 STARTS)

(CAM SOFTWARE RECOMMENDATIONS:)
(- MASTERCAM: USE "CURVE 5-AXIS" TOOLPATH)
(- FUSION 360: USE "FOLLOW PATH" STRATEGY)
(- HYPERMILL: USE "5-AXIS TANGENT PLANE" MODE)
(- EDGECAM: USE "WAVEFORM ROUGHING" ON CURVE)

(MANUAL PROGRAMMING OF FULL HELIX EXCEEDS)
(CONTROLLER MEMORY ON MOST MACHINES.)
(CAM-GENERATED CODE RECOMMENDED.)

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(  APPENDIX B: COORDINATE CONVERSION TABLE         )
(=====================================================)

(NODE POCKET POSITIONS - METRIC TO INCH)
(ORIGINAL METRIC COORDINATES IN MM)

(NODE   ANGLE   X(mm)    Y(mm)    X(inch)   Y(inch))
(1      0°      +5.000   0.000    +0.1969   0.0000)
(2      30°     +4.330   +2.500   +0.1705   +0.0984)
(3      60°     +2.500   +4.330   +0.0984   +0.1705)
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(4 90° 0.000 +5.000 0.0000 +0.1969)
(5 120° -2.500 +4.330 -0.0984 +0.1705)
(6 150° -4.330 +2.500 -0.1705 +0.0984)
(7 180° -5.000 0.000 -0.1969 0.0000)
(8 210° -4.330 -2.500 -0.1705 -0.0984)
(9 240° -2.500 -4.330 -0.0984 -0.1705)
(10 270° 0.000 -5.000 0.0000 -0.1969)
(11 300° +2.500 -4.330 +0.0984 -0.1705)
(12 330° +4.330 -2.500 +0.1705 -0.0984)

(RADIUS CHECK: SQRT(X² + Y²) = 5.000mm = 0.1969")

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(APPENDIX C: METRIC VERSION PARAMETER LIST)
(===)

(TO CONVERT PROGRAM TO METRIC G21 MODE:)

(CHANGE LINE 40: G20 → G21)
(REPLACE ALL INCH VALUES WITH MM EQUIVALENTS:)

(FACE DEPTH: -0.008" → -0.2mm)
(BORE DEPTH: -0.415" → -10.5mm)
(NODE DEPTH: -0.0394" → -1.0mm)
(HELIX RADIUS: 0.492" → 12.5mm)
(OD RADIUS: 0.591" → 15.0mm)

(ADJUST FEED RATES:)
(5 IPM → 125 mm/min)
(3 IPM → 75 mm/min)
(1 IPM → 25 mm/min)
(10 IPM → 250 mm/min)
(12 IPM → 300 mm/min)

(PECK DEPTH: Q0.08 → Q2.0)
(RETRACT: R0.1 → R2.5)

(===)
(APPENDIX D: TOOL WEAR MONITORING)
(===)

(EXPECTED TOOL LIFE FOR Ta-Ti-Au ALLOY:)
(T01 FACE MILL: 20-30 PARTS BEFORE EDGE WEAR)
(T02 DRILL: 10-15 PARTS, CHECK FLANK WEAR)

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(T03 REAMER: 5-10 PARTS, CRITICAL TOLERANCE)
(T05 PCD BALL MILL: 50+ PARTS, VERY DURABLE)
(T06 NODE DRILL: 30-40 PARTS)

(INSPECT TOOLS UNDER 10× MAGNIFICATION:)
(- FLANK WEAR >0.3mm = REPLACE)
(- CHIPPING OR CRACKING = IMMEDIATE REPLACEMENT)
(- BUILT-UP EDGE = CLEAN OR REPLACE)

(CHECK BORE DIAMETER AFTER EVERY 5 PARTS)
(IF BORE GROWS >0.002", REPLACE REAMER)

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(  APPENDIX E: TROUBLESHOOTING GUIDE              )
(=====================================================)

(PROBLEM: BORE DIAMETER OUT OF TOLERANCE)
(CAUSE: REAMER WEAR, IMPROPER FEED RATE)
(SOLUTION: REPLACE REAMER, REDUCE FEED TO 1 IPM)

(PROBLEM: POOR SURFACE FINISH ON OD)
(CAUSE: TOOL VIBRATION, EXCESSIVE FEED)
(SOLUTION: REDUCE SPINDLE SPEED TO 8000 RPM,)
(         INCREASE RIGIDITY OF SETUP)

(PROBLEM: HELIX THREADS NOT UNIFORM)
(CAUSE: INTERPOLATION ERROR, BACKLASH)
(SOLUTION: USE CAM-GENERATED CODE, CHECK)
(         MACHINE BACKLASH COMPENSATION)

(PROBLEM: NODE POCKETS NOT CONCENTRIC)
(CAUSE: WORK COORDINATE OFFSET ERROR)
(SOLUTION: RE-INDICATE PART CENTER, VERIFY G54)

(PROBLEM: PART MOVES DURING MACHINING)
(CAUSE: INSUFFICIENT CLAMPING FORCE)
(SOLUTION: INCREASE CHUCK PRESSURE, USE SOFT JAWS)

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(  DOCUMENT CONTROL                               )
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(DOCUMENT: TITAN A16 CNC PROGRAMMING APPENDIX)
(DOCUMENT NUMBER: TITAN-A16-CNC-003)
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(REVISION: 3.0)
(DATE: JANUARY 22, 2026)
(AUTHOR: MATTHEW JAMES CAMPBELL)
(APPROVED FOR PRODUCTION USE)

(REVISION HISTORY:)
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(REV 2.0 - 2026-01-10 - ADDED HELIX CODE)
(REV 3.0 - 2026-01-22 - CONTROLLER-SAFE VERSION,)
(INCH MODE, SIMPLIFIED HELIX)

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(END OF DOCUMENT 3   )
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