Complete Manufacturing Process of Stage 2 Turbine Disk of GE CT7 Engine

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Contents

1: Manufacturing Plan

The following procedure details all major steps in the manufacturing process for the Disk Turbine Stage 2, Part Number 6064T12P02. The processes are listed sequentially and follow the process planning sheet outlined in Appendix A.

1.1 Material Selection

The material used for the turbine disk is Inconel 718. Inconel 718 is a nickel-based superalloy, a similar material to that used in gas engine turbine blades [1]. Inconel 718 in particular is used over other nickel-based superalloys, such as Inconel 600 and 625, for its superior creep resistance, which is particularly needed in gas engines due to the heat and velocity at which the shaft operates [1].

Table 1: Inconel Alloy Compositions and Features [1]

Alloy	**Composition**	**Features**
Inconel 625	Nickel (58%), Chromium (20–23%), Molybdenum (8–10%), Niobium (3.15–4.15%)	Outstanding strength and toughness, excellent resistance to corrosion and oxidation, used in aerospace, marine, and chemical processing industries.
Inconel 600	Nickel (76%), Chromium (15–17%), Iron (balance)	Good oxidation and corrosion resistance at high temperatures.
Inconel 718	Nickel (50–55%), Chromium (17–21%), Iron (balance), Molybdenum (2.8–3.3%), Niobium (4.75–5.5%)	High strength and corrosion resistance at elevated temperatures, used extensively in aerospace, gas turbine engines, and oil & gas industries.

To create a microstructure that is better equipped to combat creep, a heat treatment process is used. This heat treatment process is defined and further explained in the subsequent section, *1.2 Manufacturing Procedure* [2].

1.2 Manufacturing Procedure

The manufacture of a turbine disk typically starts with a solid cylindrical piece of metal that is subjected to compression [3]. The following procedure begins with Inconel ring stock that will be subject to a sequence of different processes: forging the major geometry, machining intricate features, surface treatment, heat treatment, surface finishing, and shot peening. Throughout these stages, meticulous inspections are conducted to verify surface integrity and material properties. The following subsections describe a detailed breakdown of each process and its functionality.

Before defining the manufacturing procedure, it is important to create definitions for the various components on the finalized part. A figure containing the final part with labels is seen in Figure 1 which details both the front and back view. Surrounding the circumference of the part are dovetails at which the turbine blades are attached. Moving inwards, there are raised edges on each side with radial notches in them. There are 38 notches on the front view that align radially with each dovetail and 19 notches on the back view that align radially with every other dovetail. Continuing inwards, there is a recessed cavity before reaching angularly spaced cooling holes that continue through the entire part. On the front view of the part, further inwards, is a raised feature that contains 'coupling teeth'. Beyond that, there is another raised edge on the front view and a tapered boss on the back view.

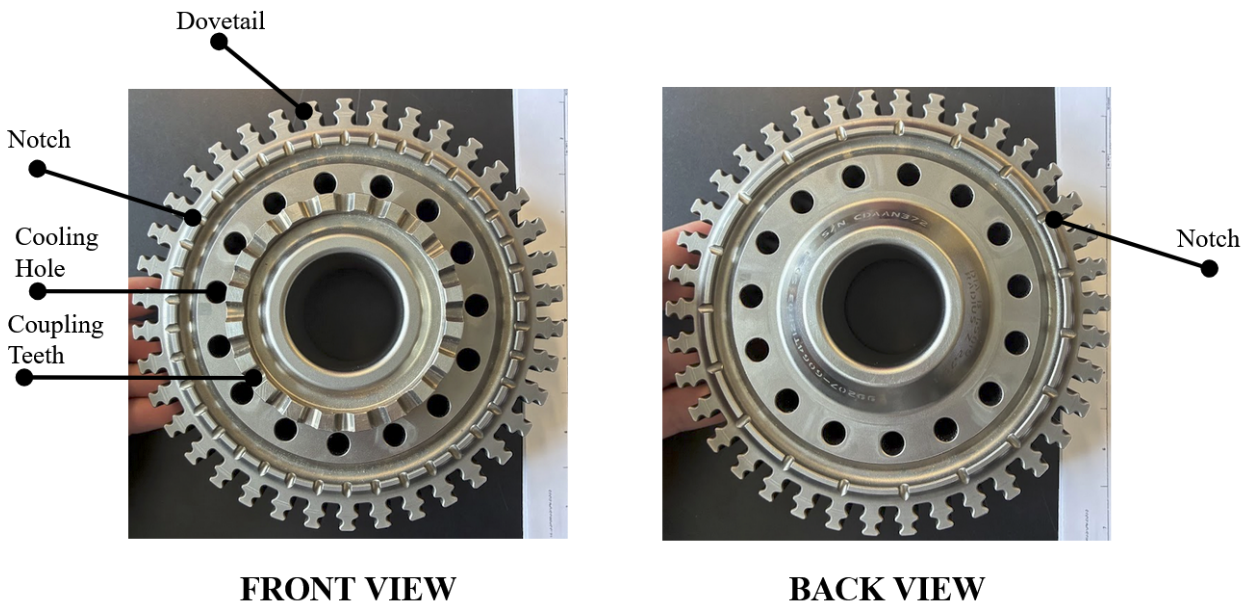

Figure 1: Final Part Labeled with Nomenclature Specific to this Report

1. **Impression Die Forging** – The initial form of the turbine disk is created through impression die forging. The stock material is ring stock, so punching the main bore is not necessary. Since impression die forging is being used to create the bulk geometry, two specialized dies, one each for the top and bottom geometries, must be created [3]. Notably, this process develops a circumferential flash that must be trimmed and machined away. This process is described in further detail later in the manufacturing procedure. The development of flash, however, is important, as it indicates the complete filling of the die cavity [3].

   The die will create the main geometry of the workpiece. This includes all major recesses and raised edges of the disk with the exception of more complex features. The dovetails, coupling teeth, cooling holes, and notches are not formed during this procedure. This mitigates the fine features that the material must flow into from forging, which decreases the forging force needed to fully pack the die cavity [3]. Additionally, the part must have positive draft angles to promote easy removal from the dies [3]. Thus, a general positive draft angle of 3° is applied to the die surfaces, and the overhang/recess below the coupling teeth is not formed. The shape of the preform is critical to the development of the inner bore of the workpiece. The top die features a cylinder that creates a defined inner diameter. This is done to mitigate the amount of machining needed, as the center bore would require a large amount of material removal.

The dimensional tolerances, surface finish, and overall quality of a forging workpiece are dictated by the quality of operation and the dies created. Typical hot impression die forging operations achieve dimensional tolerances of 0.5%-1.0% of part dimensions and a variable surface finish, depending on die quality [3]. Appendix B outlines surface finishes for major bulk deformation operations. It can be seen that forging, in less typical contexts, can achieve a surface finish of 63 μin. Most of the surface finishes will be dictated by machining operations, such as turning for all circular features. Because of this, machining allowance is needed on all dimensions of the part. Generally, machining allowance for small castings ranges from 0.08 to 0.2 inches [3]. Although the part is subject to forging, this metric was referenced when defining the machining allowance for this part. A machining allowance of 0.1 inches is used on all surfaces.

2. **Initial Geometry Inspection** – Following impression die forging, the turbine disk will exhibit surface oxidation, requiring a sufficient machining allowance for subsequent operations [4]. Therefore, it is important to verify that adequate material remains on all machinable surfaces. The initial inspection will consist of a visual examination to check for any obvious surface cracks or defects, followed by dimensional verification using calipers to ensure tolerances are met and that sufficient machining allowance is found on each main surface. Given that the outer layer of material will be removed, detailed surface inspection techniques are deferred until after machining. At that stage, dye penetrant inspection (DPI) will be used to detect any surface cracks, as described in later sections. To ensure internal material integrity, ultrasonic inspection will also be performed to detect any subsurface defects introduced during the forging process.

3. **Turning** – Inconel 718 is a difficult alloy to machine. That being said, it is entirely possible with the right tooling and machine parameters. The workflow for turning, across roughing and finishing operations, must be carefully planned out to ensure the part does not become work hardened, the tools do not become damaged, and the workpiece is not ruined. CNMG 12 04 08 inserts in fine-grain carbide with a PVD TiAlN are used. This is an insert with a hard-heat resistant coating which is essential for managing the thermal loads that tooling of Inconel 718 generates when cut. The rough pass should be at a cutting speed of about 200 ft/min with a feed rate of 0.01 in/rev at a depth of 0.05 in [5]. These conservative parameters reflect the alloy's notorious work-hardening behavior, and general difficulty to machine. For the finishing pass, cutting speed my be increased to 400 ft/min while feed is reduced to 0.002 in/rev at a 0.01 depth. This trades removal rate for accuracy and surface finish. During both passes, flood coolant delivered at high pressure right at the cutting edge is needed to

suppress edge formation and increase tool life[5].
Basic turning operations include facing the flat surfaces, turning the outer diameter (includes removing the flash), boring the inner diameter, taper turning angled surfaces, cutting grooves in the faces, filleting, and breaking and chamfering the circumferential edges of the coupling teeth and raised edges. Material must also be removed to form the recess below the coupling teeth. The most complex operation is creating the form of the recess in the inner radial side of the raised edges on both sides. Care must be taken to produce the curvature by using multiple tools with different radii, or a custom form tool. All of the turned surfaces have a specified surface roughness of 63μin, which is easily achievable in turning (see Appendix B).

4. **Milling** – While much of the geometry of the workpiece is concentric, many aspects must be milled. For milling operations on the Inconel 718 component, solid carbide end mills with a PVD TiAlN coating are employed. As in turning, hard, oxidation-resistant tooling is essential for surviving the thermal aggression Inconel directs at any cutting edge. Careful toolpath planning is necessary to maintain consistent engagement and avoid tool dwells that would instantly work-harden walls. Coolant sprayed at moderate pressure is specified, ensuring chip evacuation remains effective inside the confined notch geometries where re-cutting swarf would compromise both surface integrity and tool life [5].

   The notches are machined into the outer raised edges of the part using a ball end mill to create a diameter of 0.055 to 0.065 inches at the bottom of each notch. Cooling holes are all drilled to an intermediate diameter, and then bored in roughing and finish passes to reach a final surface roughness of 16μ in. The cooling holes are then countersunk. Specific geometry for the coupling teeth is not given in the provided drawings. Assuming the teeth have a simple profile, they can be milled as well. Otherwise, a specialized gear shaping process would be necessary. As a final step, all edges should be broken or rounded according to the specification. Given the complex contour of the dovetails, the dovetail edges should be rounded via a CNC toolpath.

5. **Broaching** – Along the circumference of the turbine disk are special grooves used to mate the turbine blades with the disk. These are called dovetail slots. To ensure proper blade-disk interfacing, the required surface roughness for these features is 63 μin. To produce these features, broaching will be employed. Broaching is a machining process used to cut internal and external surfaces, including holes, gear teeth, and splines [3]. As shown in Fig. 2, a broach is a long, multi-tooth tool that removes material through successively deeper cuts. This process is capable of achieving excellent surface finishes (up to 32 μin for typical use) and high dimensional accuracy (see Appendix B), making it optimal for cutting the dovetails. Although broaching tools are expensive, the cost is justified in high-volume, high-quality production environments.

   For this process, the turbine disk will be placed flat on either its front or back face so that machining occurs in the vertical direction. Each dovetail will be machined individually, after which the part will be radially indexed to the next position. This process will be repeated for all 38 dovetails. In a study done by Liu et al., YG3 was selected as the tool material given its desirable hardness, excellent wear resistance,

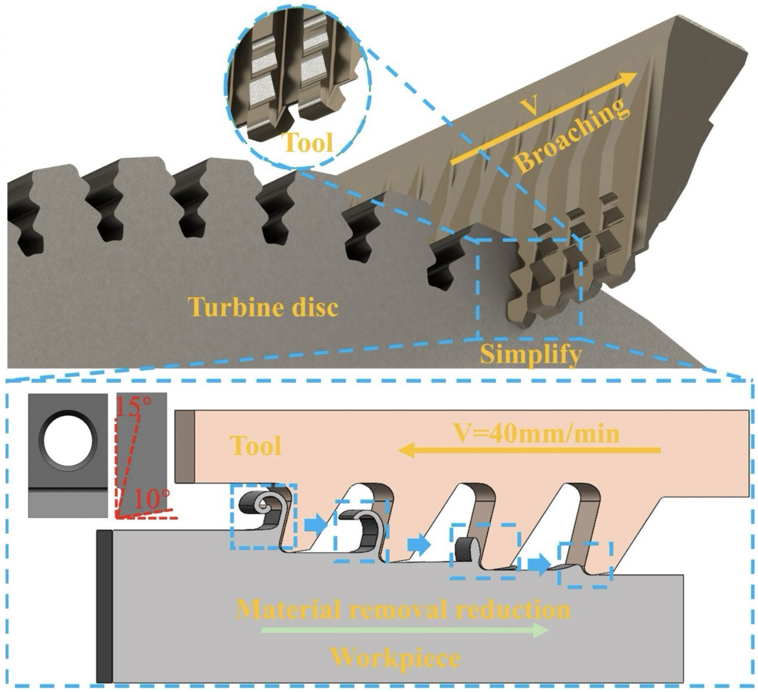

Figure 2: Schematic Diagram Showing Broaching of Turbine Disk from [6]

good toughness, and high compressive strength. These properties are necessary for minimizing tool wear and extending tool life during operations [6]. Alongside the tool material, the rake angle of 15° and flank angle of 10° reported in the study will be adopted to ensure effective cutting performance. While the cutting speed used in the reference study was relatively low given its experimental purposes, this broaching operation would use a standard industrial cutting speed on the order of 30 ft/min with a standard push broach length of 14 inches [3, 7]. Accounting for total broach displacement (14.7 inches to account for cutting), the broach return, and the indexing process (2 seconds), this results in a machining time of 262 seconds per disk. A water soluble or emulsion coolant will also be used to reduce heat generation and prevent material buildup on the cutting edges.

6. **Post-Machining Inspection** – After machining and broaching, the turbine disk must undergo comprehensive nondestructive inspection to check both surface and subsurface integrity. These processes are critical for verifying that the part will not fail when subject to high speeds, temperature, and pressure.

   For surface inspection, dye penetrant inspection (DPI) will be used on all of the machined features. This includes the dovetail slots, machined holes, as well as the larger main surfaces. DPI is particularly effective for detecting surface cracks, seams, and unwanted surface porosity that may have resulted from cutting operations [3]. Special attention will be given to geometric discontinuities such as edges and fillets, where stress concentration is the highest and crack initiation is most common. On top of DPI, eddy-current inspection (ET) will also be employed for regions prone to near-surface cracks, including the cooling holes, to detect any surface or near-surface cracks in the hole cavities.

For internal inspection, ultrasonic inspection (UT) will be utilized to detect subsurface defects and discontinuities. UT provides an extremely precise evaluation of the internal structure and is capable of revealing hidden voids or cracks, not visible through surface inspection [3]. This technique will be also applied in regions near critical elements, specifically the cooling holes, to ensure that no internal damage or defects result from machining.

7. **Heat Treatment** – One key advantage of using nickel-based superalloys as the base material is the ability to achieve a fine-tuned γ/γ' microstructure. The γ' precipitates impede the movement of dislocations while providing properties unique to the γ/γ' microstructure. The first of these is the coherent lattice interface between the γ and γ' phases; this coherency prevents the γ' precipitates from coarsening rapidly, which is beneficial as smaller, more numerous precipitates are more effective at blocking dislocations [8]. Additionally, the yield strength of the γ' phase atypically increases with temperature up to approximately 800°C [9]. Heat provides the activation energy for dislocations to cross-slip from primary slip planes to planes where movement is more restricted, forming immobile Kear-Wilsdorf locks. This allows the γ/γ' microstructure to maintain operational integrity at temperatures much higher than traditional alloys while exhibiting superior creep resistance.

   Allowing the cast metal to cool without intervention is not sufficient for creating a precise microstructure, as alloying elements remain segregated, yielding γ' precipitates that are irregular in shape and size, which reduces their effectiveness at impeding dislocation motion [10]. To dissolve these irregular precipitates from the casting process, the cast blade is heated to below the melting point of the material but above the γ' solvus temperature, producing a single-phase γ alloy [10]. Once single-phase, the blade is quenched, causing the $L1_2$ γ' microstructure to nucleate. Because the cast is quenched rather than slow-cooled, this results in many small γ' precipitates that do not have time to grow by diffusion. To grow the γ' precipitates to a size more effective at impeding dislocation motion, the blade is held at an elevated temperature, typically around 1000–1100°C [11].

8. **Shot Peening** – Before the final inspection, the component undergoes shot peening across specified surfaces, with intensity varying by zone as called out by the drawing, values ranging from 0.002-0.012, with certain areas requiring select intensities to target specific fatigue life or residual stress requirements. Areas with more stress concentration demand more aggressive peening to drive compressive residual stress deep enough to surpress crack initiation. Masking is used between zones to maintain the integrity of each intensity specification, and prevent overpeen on certain surfaces, as the drawing specifically notes certain areas should not be overpeened.

9. **Final Inspection** – One final inspection of the part should be conducted following the completion of the post machining inspection, heat treatments, and shot peening. This inspection is necessary given that the aging cylce and shot peening both change the

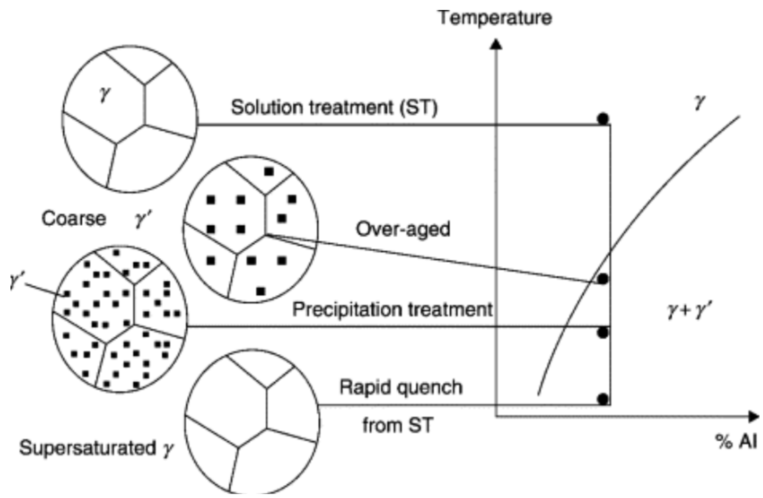

Figure 3: Schematic of Heat Treatment for Nickel-Based Superalloys Showing [2]

part measurably. Critical dimensions are re-evaluated in full including but not limited to: the inner and outer diameters, cooling hole sizes, dovetail dimensions, and mount geometries. Surface finishes may be ignored at this step, as the finishes given in the drawings apply to the workpiece before the shot peening has occured. Once again, DPI is applied to the part surfaces, UT to the entire geometry as a final subsurface check, and ET will be applied to the cooling holes to ensure there are no cracks on or near the surfaces. Only upon completion of all dimensional checks is the component approved for release, being granted all proper machining records and inspection certifications.

2: Manufacturing Cost

The associated cost for a batch of 25 turbine disks has two major components: overhead costs on material and outsourced operations, and labor costs associated with machine shop operations. For purposes of this manufacturing plan, it is assumed that production cannot be parallelized (i.e., many workpieces cannot be machined simultaneously). Therefore, the total cost for the entire batch is that of a single part multiplied by the batch size. The total cost per piece is described by the following equation, where C_p is the cost per piece, C_m is the cost of machining, C_l is the cost of labor, C_t is the tooling cost, and C_a is the cost of additional expenditures including stock material and outsourced operations.

$$C_p = C_m + C_l + C_t + C_a$$

All equations and concepts used in the following cost derivation are drawn from *Manufacturing Processes for Engineering Materials* by Kalpakjian and Schmid unless otherwise noted [3].

2.1 Tooling Cost

The tooling cost is given by the following expression, where N_i is the number of parts machined per insert, N_f is the number of parts that can be machined per insert face, $L_m =$

\$100 /hr is the labor cost per operator, B_m is the machine burden rate, t_c is the time required to change an insert, t_i is the time required to index the insert, and D_i is the depreciation cost of the insert.

$$C_t = \frac{1}{N_i}\left[t_c(L_m + B_m) + D_i\right] + \frac{1}{N_f}\left[t_i(L_m + B_m)\right]$$

The burden rate encompasses the depreciation and maintenance of the machine. For a small batch of 25 parts, the burden of the machine is assumed negligible; therefore $B_m = 0$.
To find the number of parts that can be machined per insert face, N_f, the tool life must first be calculated. Tool life is given by the Taylor tool life equation, where t is the tool life, V is the cutting speed, and C and n are material constants.

$$t = \left(\frac{C}{V}\right)^{1/n}$$

Carbide tooling is required for this application, as HSS tools lack sufficient hardness for machining Inconel 718. For carbide tools on Inconel 718, the material constants are $C = 240$ m/min and $n = 0.25$ [12]. Cutting speeds vary by operation: a rough turning speed of 60 m/min and a finish turning speed of 120 m/min are used, consistent with published recommendations for carbide tooling on nickel superalloys. For milling, rough and finish speeds of 80 m/min and 140 m/min are used respectively. The uncapped tool lives are computed as follows:

$$t_{\text{rough, turn}} = \left(\frac{240}{60}\right)^{1/0.25} = (4.000)^4 = 256 \text{ min} \qquad \text{Rough Turning Tool Life}$$

$$t_{\text{finish, turn}} = \left(\frac{240}{120}\right)^{1/0.25} = (2.000)^4 = 16.0 \text{ min} \qquad \text{Finish Turning Tool Life}$$

$$t_{\text{rough, mill}} = \left(\frac{240}{80}\right)^{1/0.25} = (3.000)^4 = 81.0 \text{ min} \qquad \text{Rough Milling Tool Life}$$

$$t_{\text{finish, mill}} = \left(\frac{240}{140}\right)^{1/0.25} = (1.714)^4 = 8.64 \text{ min} \qquad \text{Finish Milling Tool Life}$$

Because tool life predictions beyond 30 minutes become unreliable in practice due to unpredictable wear mechanisms, chipping, and thermal fatigue in nickel superalloy machining, any computed tool life exceeding 30 minutes is capped at $t_{\max} = 30$ min. The rough turning tool life of 256 min and the rough milling tool life of 81 min both exceed this threshold and are therefore capped. The adopted tool lives are:

$$t_{\text{rough, turn}} = 30 \text{ min} \qquad \text{(capped from 256 min)}$$
$$t_{\text{finish, turn}} = 16.0 \text{ min}$$
$$t_{\text{rough, mill}} = 30 \text{ min} \qquad \text{(capped from 81 min)}$$
$$t_{\text{finish, mill}} = 8.64 \text{ min}$$

Broaching tools follow the same Taylor equation, but with different material constants and a lower cutting speed, reflecting the more aggressive engagement of the broach teeth. For carbide broaching tools, $C = 100$ m/min and $n = 0.10$, with a typical cutting speed of $V = 9.1$ m/min (30 ft/min) [13]. This gives:

$$t_{\text{broach}} = \left(\frac{100}{9.1}\right)^{1/0.10} = (10.989)^{10} = 25{,}390 \text{ min} \qquad \text{Broaching Tool Life}$$

The broaching tool life of 25,390 min far exceeds the 30-minute cap and is therefore set to $t_{\text{broach}} = 30$ min.

The machining time t_m for each operation is calculated using the expressions below, where f is the feed rate, l is the axial length of cut, D is the workpiece diameter, l_c is the tool approach length, l_t is the broach length, and l_w is the workpiece length.

$$t_m = \frac{\pi l D}{fV} \qquad \text{Time for Turning}$$
$$t_m = \frac{l + 2l_c}{V} \qquad \text{Time for Milling}$$
$$t_m = \frac{l_t + l_w}{V} \qquad \text{Time for Broaching}$$

Milling is performed on the 57 notches and 20 coupling teeth. Invoking the simplification $l \gg l_c$ and using $l = 0.23$ in $= 0.00584$ m, the machining time based purely on cutting speed is:

$$t_{m,\text{mill, rough}} = \frac{77 \cdot 0.00584}{80} = 0.00562 \text{ min}$$
$$t_{m,\text{mill, finish}} = \frac{77 \cdot 0.00584}{140} = 0.00321 \text{ min}$$

However, this expression neglects feed limitations and assumes a single-pass cut. In practice, milling time is governed by feed per tooth and multiple passes required to achieve final geometry, particularly in nickel-based superalloys. To account for these effects, a correction factor of $k = 50$ is applied, which is consistent with typical CNC milling cycle times for small features in Inconel alloys.

$$t_{m,\text{mill, rough}} = 50 \times 0.00562 = 0.281 \text{ min}$$
$$t_{m,\text{mill, finish}} = 50 \times 0.00321 = 0.160 \text{ min}$$

Turning is the dominant machining operation, as the majority of the part's features are axisymmetric. Feed rates from Section 1.2 are $f_{\text{rough}} = 0.01$ in/rev $= 2.54 \times 10^{-4}$ m/rev and $f_{\text{finish}} = 0.002$ in/rev $= 5.08 \times 10^{-5}$ m/rev, with corresponding cutting speeds of 60 m/min and 120 m/min. Using a workpiece outer diameter of $D = 0.3$ m and taking the total axial turned length l as equivalent to the machining allowance of 0.1 in $= 0.00254$ m, the turning times are:

$$t_{\text{rough, turn}} = \frac{\pi \cdot 0.00254 \cdot 0.3}{2.54 \times 10^{-4} \cdot 60} = \frac{2.394 \times 10^{-3}}{1.524 \times 10^{-2}} = 0.1572 \text{ min}$$

$$t_{\text{finish, turn}} = \frac{\pi \cdot 0.00254 \cdot 0.3}{5.08 \times 10^{-5} \cdot 120} = \frac{2.394 \times 10^{-3}}{6.096 \times 10^{-3}} = 0.3927 \text{ min}$$

The broaching time was calculated in Section 1.2 and equals $t_{m,\text{broach}} = 262$ s $= 4.36$ min per workpiece. With all machining times established, the number of parts per insert face N_f can be calculated for each operation:

$$N_{f,\text{turn}} = \frac{t_{\text{rough, turn}}}{t_{m,\text{rough, turn}}} + \frac{t_{\text{finish, turn}}}{t_{m,\text{finish, turn}}} = \frac{30}{0.1572} + \frac{16.0}{0.3927} = 231.5 \qquad \text{(Turning)}$$

$$N_{f,\text{mill}} = \frac{t_{\text{rough, mill}}}{t_{m,\text{rough, mill}}} + \frac{t_{\text{finish, mill}}}{t_{m,\text{finish, mill}}} = \frac{30}{0.281} + \frac{8.64}{0.160} = 160.76 \qquad \text{(Milling)}$$

$$N_{f,\text{broach}} = \frac{t_{\text{broach}}}{t_{m,\text{broach}}} = \frac{30}{4.36} = 6.88 \qquad \text{(Broaching)}$$

The number of parts per insert, N_i, follows from $N_i = m \cdot N_f$, where m is the number of usable faces per insert. The turning operation uses a CNMG insert with $m = 4$ indexable faces. Milling uses a solid carbide end mill with no indexable faces, so $m = 1$. Broaching similarly uses a solid tool with $m = 1$.

$$N_{i,\text{turn}} = 4 \cdot 231.5 = 926.0 \qquad \text{Turning}$$
$$N_{i,\text{mill}} = 1 \cdot 160.76 = 160.76 \qquad \text{Milling}$$
$$N_{i,\text{broach}} = 1 \cdot 6.88 = 6.88 \qquad \text{Broaching}$$

The times required to change and index cutting tools are summarized in Table 2. Note that milling and broaching tools have no indexable faces, so no indexing time applies.

Table 2: Summary of Tool Change and Insert Indexing Times by Operation [3, 14]

Operation	**Index Time, t_i (min)**	**Change Time, t_c (min)**
Turning	1–2	3–5
Milling	—	3–7
Broaching	0.03	15–30

Midpoint values are used for all ranges: $t_{c,\text{turn}} = 4$ min, $t_{i,\text{turn}} = 1.5$ min, $t_{c,\text{mill}} = 5$ min, $t_{c,\text{broach}} = 22.5$ min, $t_{i,\text{broach}} = 0.03$ min. The cost per insert D_i is $250 for turning, $20 for milling, and $4,000 for broaching [15–17]. With all quantities defined, the tooling costs for each operation are:

$$\begin{aligned}
C_{t,\text{turn}} &= \frac{1}{926.0}\left[4 \cdot \tfrac{100}{60} + 250\right] + \frac{1}{231.5}\left[1.5 \cdot \tfrac{100}{60}\right] \\
&= \frac{1}{926.0}\left[6.667 + 250\right] + \frac{1}{231.5}\left[2.500\right] = 0.2774 + 0.01080 = \$0.288
\end{aligned}$$

$$\begin{aligned}
C_{t,\text{mill}} &= \frac{1}{8{,}030}\left[5 \cdot \tfrac{100}{60} + 20\right] \\
&= \frac{1}{160.76}\left[8.333 + 20\right] = \frac{28.33}{8{,}030} = \$0.1765
\end{aligned}$$

$$\begin{aligned}
C_{t,\text{broach}} &= \frac{1}{6.88}\left[22.5 \cdot \tfrac{100}{60} + 4{,}000\right] + \frac{1}{6.88}\left[0.03 \cdot \tfrac{100}{60}\right] \\
&= \frac{1}{6.88}\left[37.5 + 4{,}000\right] + \frac{1}{6.88}\left[0.05\right] = 586.8 + 0.007 = \$586.8
\end{aligned}$$

$$\boxed{C_{t,\text{total}} = C_{t,\text{turn}} + C_{t,\text{mill}} + C_{t,\text{broach}} = \$0.288 + \$0.1765 + \$586.8 \approx \$587.26 \text{ per part}}$$

The broaching tool dominates tooling cost due to its high unit cost ($4,000) and relatively low N_i of 6.88 parts per tool, a consequence of the long per-part broaching time of 4.36 min relative to the capped 30-min tool life.

2.2 Machining Costs

The machining costs C_m are given by the following expression, where t_m is the machining time, L_m = $100 /hr is the labor cost per operator, and B_m is the machine burden rate, assumed negligible for this batch size.

$$C_m = t_m(L_m + B_m)$$

The total machining time is:

$$t_{\text{total}} = 0.1572 + 0.3927 + 0.00562 + 0.00321 + 4.36 = 4.918 \text{ min}$$

$$\boxed{C_m = \left(\frac{4.918 \text{ min}}{60 \text{ min/hr}}\right)(\$100 \text{ /hr}) = \$8.20 \text{ per part}}$$

2.3 Labor Costs

The labor costs C_l are given by the following expression, where t_l is the total time for loading and unloading operations across all machines.

$$C_l = t_l(L_m + B_m)$$

The various loading and unloading times are summarized in Table 3.
Using midpoint values for each range, the total loading and unloading time is:

$$t_l = 4 + 7.5 + 7.5 + 2 = 21 \text{ min}$$

$$\boxed{C_l = \frac{21 \text{ min}}{60 \text{ min/hr}}(\$100 \text{ /hr}) = \$35.00 \text{ per part}}$$

Table 3: Summary of Loading and Unloading Times [14, 18, 19]

Machine	Loading and Unloading Time	Operation
Forging	3–5 min per cycle	Stock into/from press + flip
Turning	5–10 min total	Chuck, indicate, re-chuck
Milling	5–10 min total	Fixture, indicate, re-fixture
Broaching	1–3 min	Loading/unloading

2.4 Additional Costs

In addition to the machining-related costs above, several further expenditures must be accounted for in the total part cost.

Raw Material

Raw Inconel 718 ring stock costs between \$16.58/kg and \$24.88/kg [20]. The stock volume is approximated as a washer geometry with the outer and inner diameters of the final part and a thickness equal to the forging preform height, which provides a conservative estimate of material consumption even accounting for flash removal.

$$V_{\text{stock}} = \frac{\pi}{4}(D_o^2 - D_i^2)\,h \approx 0.002\text{ m}^3$$

Multiplying by the density of Inconel 718, $\rho = 8200$ kg/m^3 [21], the stock mass and material cost are:

$$C_{\text{material}} = \rho \cdot V_{\text{stock}} \cdot \text{Cost/Unit} = \$408 \text{ per part}$$

Forging Dies

The impression dies represent a substantial fixed cost that must be amortized across the batch. Die costs vary widely based on complexity, tolerance requirements, and material; a typical range is \$5,000–\$50,000 or more [22]. Given the complexity of this forging, the exposure to a nickel-based superalloy, and the tight dimensional tolerances required, a cost at the upper end of this range is expected. Amortized over the batch of 25 parts [3, 22]:

$$C_{\text{die}} = \frac{\$50{,}000}{25} = \$2{,}000 \text{ per part}$$

Outsourced Processes

Shot peening and heat treatment are specialized processes that require dedicated equipment and certification, and are therefore outsourced. According to Aircraft Materials, the heat treatment process takes 20–26 hours to run; assuming the full batch of 25 parts occupies one furnace load [23]:

$$C_{\text{heat}} = \frac{\$7{,}500}{25} = \$300 \text{ per part}$$

For shot peening, aeronautical engine manufacturers report a per-part cost of approximately \$500 for turbine components when outsourced to a certified vendor [24]. Given that the turbine disk requires zoned Almen intensities, masking between zones, and NADCAP-accredited process control, this figure is adopted as the per-part shot peening cost:

$$C_{\text{peen}} = \$500 \text{ per part}$$

The combined outsourced cost per part is therefore:

$$C_{\text{outsource}} = C_{\text{heat}} + C_{\text{peen}} = \$300 + \$500 = \$800 \text{ per part}$$

Inspection

Comprehensive nondestructive inspection, including DPI, UT, and ET, requires certified technician time and consumables. According to an NDT inspection rate guide for 2026, the average cost per inspection for DPI, UT, and ET are roughly \$100, \$45, and \$130 respectively [25]. The total inspection cost per part is:

$$C_{\text{inspection}} = 3 \cdot \$100 + 2 \cdot \$45 + 2 \cdot \$130 = \$650 \text{ per part}$$

Combining all additional costs:

$$\boxed{C_a = C_{\text{material}} + C_{\text{die}} + C_{\text{outsource}} + C_{\text{inspection}} = \$408 + \$2{,}000 + \$800 + \$650 = \$3{,}858 \text{ per part}}$$

2.5 Final Cost

With all cost components determined, the total cost per turbine disk is:

$$\boxed{C_p = C_m + C_l + C_t + C_a = \$8.20 + \$35.00 + \$587.26 + \$3{,}858 = \$4{,}488.46 \text{ per part}}$$

Multiplying by the batch size gives the total batch cost:

$$\boxed{C_{\text{batch}} = 25\, C_p = \$112{,}211.50}$$

It should be noted that this remains a likely underestimate. Factors not considered include bureaucratic documentation, shipping to and from heat treatment and peening facilities, machine setup and qualification time, and the many other inefficiencies inherent to the production of certified aerospace turbine components.

3: Defect Mitigation

To minimize the risk of critical defects, targeted inspection and process control measures were implemented immediately following machining operations. In particular, ultrasonic inspection and eddy-current inspection were conducted directly after machining, with focused evaluation in regions surrounding the cooling holes. These features represent areas of elevated concern due to their geometry and susceptibility to stress concentrations and machining-induced damage, as seen by the July 2, 1996 failure. Early-stage inspection enables the identification of surface, near-surface, and entirely subsurface defects such as microcracks and material discontinuities before proceeding to subsequent processing steps, thereby reducing the likelihood of propagating defects through the remainder of the manufacturing process.

To further mitigate defect formation in the cooling holes, a two-step machining strategy was employed. The holes were first drilled to establish an intermediate internal diameter, followed by a boring operation to achieve the final dimension. Drilling on its own has a higher risk of creating cracks, so this approach reduces the likelihood of machining-induced tearing or microcrack formation, improves the dimensional accuracy, and produces a superior surface finish. A target surface roughness of approximately 16 μin was specified to minimize stress concentrations and improve fatigue resistance in these critical features.

Finally, shot peening was applied as a post-machining surface treatment to enhance fatigue performance and suppress crack initiation. By introducing compressive residual stresses at the surface, shot peening counteracts tensile stresses that can lead to crack formation under cyclic loading. Zoned peening intensities were utilized to tailor the residual stress profile based on local stress concentrations, with higher intensities applied in critical regions such as the dovetail slots. This targeted approach ensures improved durability and reliability of the turbine disk under the intense service conditions.

References

[1] Technology, Seather. "Inconel 600, 625, and 718 Side-by-Side Comparison."

[2] Álvarez Tejedor, T., Singh, R. and Pilidis, P. *Modern Gas Turbine Systems*. Woodhead Publishing (2013).

[3] Kalpakjian, Serope and Schmid, Steven R. *Manufacturing processes for engineering materials*, sixth edition ed. Pearson Education, Boston (2017).

[4] Zhao, Chunling, Lv, Shijie, Peng, Wenya, Yang, Qinzheng, Li, Wei, Cao, Xinpeng, Geng, Yongxiang, Hu, Xiaoan and Zheng, Haizhong. "Research on oxidation behavior of Inconel 718 nickel-based superalloy by laser powder bed fusion." *Materials Today Communications* Vol. 52 (2026): p. 115115. DOI 10.1016/j.mtcomm.2026.115115. Accessed 2026-05-05, URL `https://www.sciencedirect.com/science/article/pii/S235249282600499X`.

[5] MW Alloys. "How to Machine Inconel 718: Methods for Turning, Milling, Drilling." URL `https://www.mwalloys.com/how-to-machine-inconel-718-methods-for-turning-milling-drilling/`. Section 4, 5, and 10, Accessed: May 4 2026.

[6] Liu, Weiguang, Meng, Zhen, Ni, Jing, Liu, Guozhen, Xu, Fugen, Lou, Bokai, Wang, Baotao and Wu, Xinghua. "Investigation on the microstructural evolution of machined surface for broaching GH4169 under critical State." *The International Journal of Advanced Manufacturing Technology* Vol. 142 No. 7 (2026): pp. 4145–4157. DOI 10.1007/s00170-026-17436-8. URL `https://doi.org/10.1007/s00170-026-17436-8`.

[7] "Inconel 718 Machinability - Leading Supplier of Special Metal Products in China." (2025). Accessed 2026-05-05, URL `https://ssmalloys.com/inconel-718-machinability/`. Section: Blog & News.

[8] Reed, R.C. *The Superalloys: Fundamentals and Applications*. Cambridge University Press (2006).

[9] Takeuchi, S. and Kuramoto, E. "Temperature and orientation dependence of the yield stress in Ni3Al." *Acta Metallurgica* Vol. 21 No. 4 (1973): pp. 415–425.

[10] Müller, L., Glatzel, U. and Feller-Kniepmeier, M. "Thermodynamics and kinetics of phase transformations in Ni-base superalloys." *Acta Materialia* Vol. 48 No. 11 (2000): pp. 2731–2745.

[11] Caron, P. and Khan, T. "Influence of microstructure on the creep properties of a nickel-based single crystal superalloy." *Materials Science and Engineering* Vol. 61 (1983): pp. 173–184.

[12] Karandikar, Jaydeep M., Abbas, Ali E. and Schmitz, Tony L. "Tool life prediction using bayesian updating. Part 1: Milling tool life model using a discrete grid method." *Precision Engineering* Vol. 38 No. 1 (2014): pp. 9–17. DOI 10.1016/j.precisioneng.2013.06.006.

[13] Klocke, F., Döbbeler, B. and Seimann, M. "Dry Broaching Using Carbon Free Steel as Tool Material." *Procedia CIRP* Vol. 46 (2016): pp. 496–499. DOI 10.1016/j.procir.2016.04.076.

[14] DeGarmo, E. Paul, Black, J. T. and Kohser, Ronald A. *Materials and Processes in Manufacturing*, 9th ed. Wiley (2003).

[15] MSC Industrial Direct Co., Inc. "Carbide Turning Insert CNMG 120408." https://www.mscdirect.com/product/details/10799120. Accessed: May 6, 2026.

[16] "Search." Accessed 2026-05-06, URL https://www.carbideanddiamondtooling.com/search?addedcart=1&itemid=646513&itemid=646513&lt_c=1&quickcart=1&qc_action=quickcart&itemadd=7503&query=broach.

[17] McMaster-Carr. "TiAlN-Coated Ball End Mills." https://www.mcmaster.com/products/end-mills/finish titanium-aluminum-nitride-tialn-coated/cut-style ball/. Accessed: May 6, 2026.

[18] CNC Optimization. "Estimate Machining Time Fast: Free CNC Operations Tool." URL https://www.cncoptimization.com/calculators/machining-time/. Accessed: 2026.

[19] Gaodelong Trade. "What is the Forging Cycle Time of a Horizontal Forging Machine?" URL https://www.gdlmachinery.com/blog/what-is-the-forging-cycle-time-of-a-horizontal-forging-machine-2460897.html. Accessed: 2026.

[20] Kollová, Alena and Pauerová, Katarína. "Superalloys - Characterization, Usage and Recycling." *Manufacturing Technology* Vol. 22 No. 5 (2022): pp. 550–557. DOI 10.21062/mft.2022.070.

[21] Special Metals Corporation. "INCONEL alloy 718." Technical Data Sheet SMC-045. Special Metals Corporation. 2007. URL https://www.specialmetals.com/assets/documents/alloys/inconel/inconel-alloy-718.pdf. Definitive manufacturer's datasheet.

[22] Walkson. "How Much Does Closed Die Forging Typically Cost?" (2024). URL https://www.walkson.com/how-much-does-closed-die-forging-typically-cost.html. Accessed: 2026-05-05.

[23] Aircraft Materials. "Nickel Alloy 718 / Inconel 718 (UNS N07718)." URL https://www.aircraftmaterials.com/data/nickel/718.html. Accessed: 2026.

[24] Nice Abrasive. "Shot Peening: Principles, Applications, and Industrial Practices." URL https://www.niceabrasive.com/shot-peening-principles-applications-and-industrial-practices/. Accessed: 2026.

[25] "Find NDT Inspection Firms Near You (2026)." Accessed 2026-05-06, URL https://ndtintel.com/.

A: Process Planning Sheet

Route Sheet : XYZ Machine Shop Inc.			
Part No. **6064T12P02**	Part Name CT7 Turbine Disk	Planner W. Fischer	Checked by: S. Mard.
Material **Inconel 718**	Stock Size Ring Stock	Comments: Batch size 25 parts	

No.	Operation Description	Dept.	Machine	Tooling	Setup	Std.
1	Impression die forge Inconel 718 ring stock to near-net-shape turbine disk; trim circumferential flash	Forge	F01	G0810	1.0 hr	5.2 min.
2	Initial geometry inspection: visual check for surface cracks, dimensional verification with calipers, ultrasonic inspection for subsurface forging defects	Insp.	—	Calipers, UT probe	0.5 hr	15.0 min.
3	Rough and finish turn all axisymmetric features: face flat surfaces, turn OD, bore ID, taper turn angled surfaces, cut grooves, fillet and chamfer edges; form recess below coupling teeth	Lathe	L45	CNMG 120408 carbide insert	0.7 hr	3.0 min.
4	Mill 57 radial notches into outer raised edges; drill then bore and countersink 20 cooling holes to final , Ra = 16 μin. Break and round edges	Mill	M32	Carbide ball end mill, TiAlN; carbide boring bar	0.7 hr	6.2 min.
5	Broach 38 dovetail slots around circumference; index radially between each slot; apply emulsion coolant	Broach	B10	YG3 carbide push broach, 14 in	1.5 hr	4.8 min.

(continued on next page)

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No.	Operation Description	Dept.	Machine	Tooling	Setup	Std.
6	Post-machining inspection: DPI on all machined surfaces; ET on cooling holes; UT on full geometry for subsurface defects	Insp.	—	DPI kit, ET probe, UT probe	0.5 hr	20.0 min.
7	Heat treatment: solution treat above γ' solvus, rapid quench, precipitation age at 1000–1100°C to develop γ/γ' microstructure (outsourced)	H.T.	—	Furnace (outsourced)	—	20–26 hr
8	Shot peen specified surfaces at zoned Almen intensities (0.002–0.012); apply masking between zones; do not overpeen designated surfaces (outsourced)	Peen	—	Shot peen equip. (outsourced)	—	2.0 hr
9	Final inspection: reverify all critical dimensions (ID, OD, cooling holes, dovetails); DPI, UT, and ET; certify and release	Insp.	—	Calipers, DPI kit, UT probe, ET probe	0.5 hr	20.0 min.

B: Table of Machining Operations and Associated Surface Finish

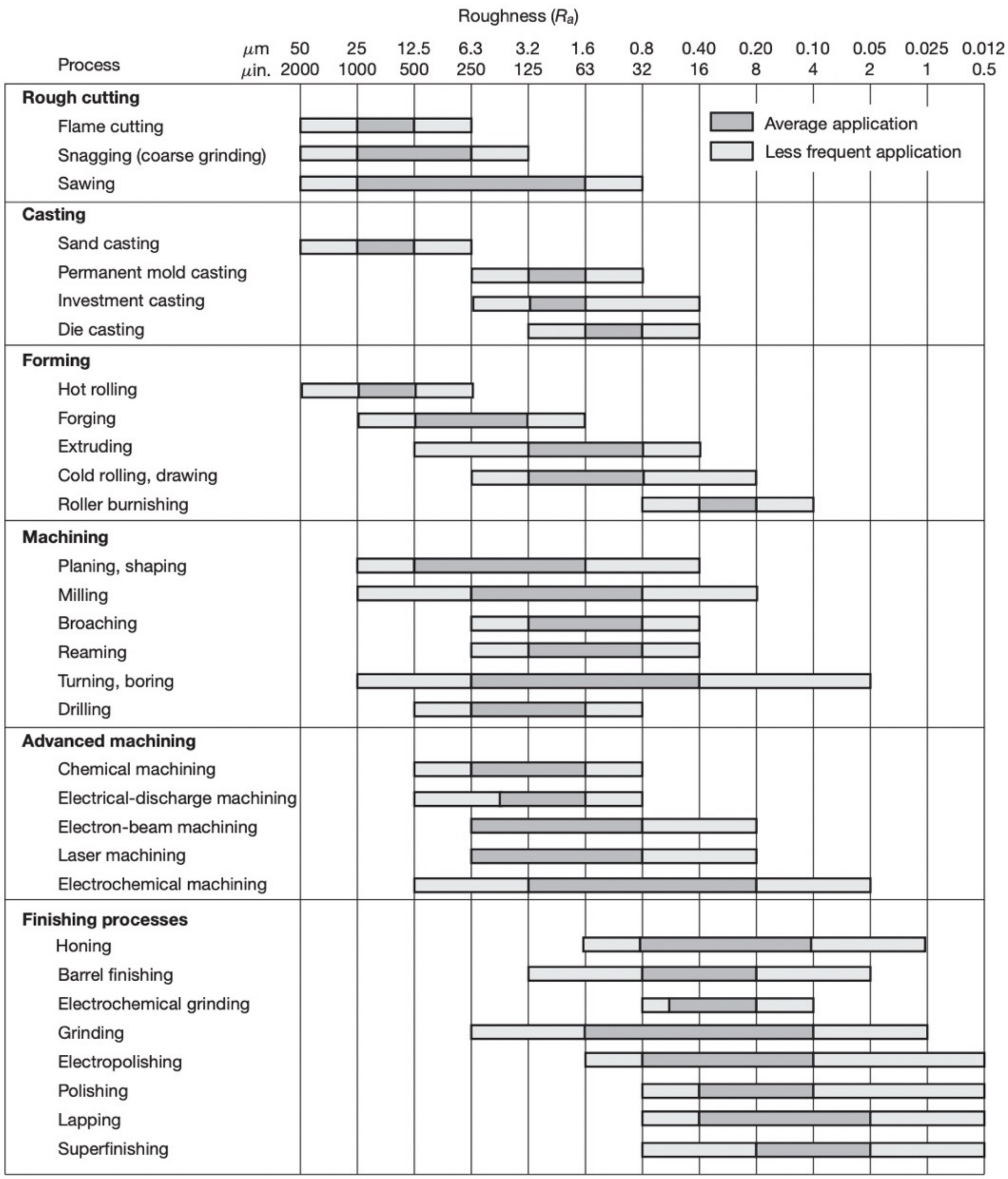

Figure 4: Range of Surface Roughness Obtained in Various Machining Processes [3]