AUTODESK UNIVERSITY

DE124929: Machining Processes for High-Temperature Aerospace Alloys

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Learning objectives:

- Find out about the work of the Autodesk Advanced Consulting team based in Birmingham, UK.
- See how Autodesk software can be combined to solve complex engineering problems.
- Learn about subtractive manufacturing processes from real-world industrial examples.
- Explore the types of manufacturing challenges present in the aerospace industry.

Class Description:

The aerospace industry has always necessitated a high degree of precision - be that in the aerofoil designs of the wings or the complex electronics on board. Designs may be as detailed as possible, but these ideas need to be accurate when they become a reality. This class will provide an insight into how certain aerospace parts are manufactured, such as bladed disks (blisks) for a turbine. Blisks often need to be machined near-perfectly, as any change in geometry has the chance to drastically reduce the fuel efficiency of an entire system. They are also usually created from incredibly strong materials like Titanium or Inconel – further increasing the difficulty of manufacture. The Autodesk Advanced Consulting team in Birmingham, UK has a lot of experience with this sort of process, working with a wide variety of customers within the industry. We will share some of the experiences we have encountered over recent years and how their related engineering challenges were overcome.

Foreword

An Introduction to Autodesk Advanced Consulting

One might be forgiven for assuming that the majority of manufacturing tasks are handled in the same way. Generally, they either involve cutting something out of a big block, adding small bits of material to get the shape you want, or a little of both. However, engineering is full of niche industries which each demand a particular approach to their associated manufacturing problems. There might be unique ways to reduce stress within a part or decrease cycle time. Slight changes in geometry, material, hardware or required tolerance could necessitate an entirely different methodology. How to adapt to these changes is often something that can only be learnt through experience, working with the same types of parts year upon year.

Occasionally, companies will encounter situations where they do not have the required knowledge of how to approach a problem, or they simply do not have the resources to devote to it. Consultancy services such as Autodesk Advanced Consulting (AAC) are often used for their wide-ranging expertise. Because consultants work with a large number of different customers, they often have a diverse array of experience across many industries.

AAC is no different, able to provide an end-to-end solution from design and optimisation to factory automation and integration. Having been involved in projects within the Aerospace, Automotive, Biomedical and Consumer Products industries, AAC is capable of providing effective solutions for a broad array of problematic tasks. This document intends to present an insight as to the types of issue previously faced by the subtractive manufacturing team of AAC, how those issues were resolved and how those solutions might be relevant to other applications. This will be done with a focus on the aerospace industry and the considerations that must be made for the materials and quality of product required.

Background

Manufacturing for the Aerospace Industry

Commercial, air-based travel is a major part of modern society, with over 8 million people supporting the industry as passengers every single day (IATA, 2013). There are 100 nations worldwide with an active military Air Force, some comprising of thousands of aircraft (NationMaster, 2003-2017). The year of 2016 saw a total of 85 known spacecraft launches, the third highest total in history (Spaceflight 101, 2016). With these numbers, it is fair to say that anything Aerospace-related must be both competitive and lucrative. In fact, the top 100 companies in the sector managed a revenue of $709 billion in 2016, an increase of $20 billion over the previous year (Thompson, 2017).

With so many flights taking to the skies each day, any change in the design or manufacture process which improves flight efficiency has the potential to save airlines billions of dollars' worth of fuel. A new concept that shaves 0.1% from the running costs might be recorded as a marvellous advancement. However, if the concept in question cannot be realised as a physical part with the utmost accuracy then the design engineer's hard work could be rendered redundant. This makes manufacturing for the aerospace industry an incredibly demanding task, with high levels of precision essential at every stage. Extremely fine surface finishes are required so as to not hinder aerodynamic performance. If material thicknesses are not exact the part could bend out of shape under high forces or weigh an aircraft down. There are a great many considerations to take into account before even starting the manufacturing process.

High-Temperature Alloys

Traditionally, most of the parts used within an aircraft are manufactured subtractively. Although some research is being conducted into the use of additive manufacture when producing aerospace parts, it is still a relatively untested technology within the industry. Conversely, machining is a much more proven method. Driven by the incredible amount of money invested in aerospace and with the safety of consumers being paramount, the reliability of this machining is a key factor. There are generally two types of material that are machined to produce parts:

- Light-weight materials - used in non-vital areas as part of the aircraft structure
- Heavier, stronger metal alloys - used in areas that will be subjected to high forces and/or high temperatures.

The lighter materials mentioned above might consist of carbon-reinforced composites, or low-density alloys such as those with a high percentage of aluminium. On the other hand, in areas where the working conditions would be harsher, Titanium-based alloys or high-Nickel-content steels are often used. Materials such as Waspaloy, Inconel and René are commonly utilised in parts of the engine for exactly this reason. Alloys like these that exhibit a high level of performance in multiple aspects are known generally as superalloys.

Placing a block of material into a machine tool and cutting it requires a great many conditions to be considered. Firstly, the interaction between the cutting tool and workpiece (block of material to be cut) as one moves while in contact with the other can have two primary, physical effects – friction and abrasion. Friction is the name of the force that opposes the relative motion of two objects. Where friction is present heat will be generated, with the amount of heat proportional to the friction between the two objects. In turn, the degree to which friction will be observed is dependent on the material of which each object comprises. In machining, large quantities of friction in the cutting zone are generally undesirable as the heat can alter a material's properties. A relatable observation of this is with clay, which permanently changes after it has been heated. The higher a material's **thermal conductivity**, the more adept it is at distributing heat throughout its shape, away from the cutting zone.

While friction leads to the generation of heat, abrasion describes the wear experienced by materials as they move against each other. This is usually produced by one material being harder than the other, but is also affected by how coarse or adhesive a surface is. A high **abrasiveness** can cause excessive tool wear or poor surface finishes.

The difference between the two phenomena can be reproduced simply by using one's hands. Warmth can be generated by rubbing two palms together rapidly, an indication of friction. However, if one palm were to be replaced with a set of fingernails the overriding sensation would be pain as the softer material of the palm wears away due to abrasion. In each interaction, both abrasion and friction will be present to some degree (for example, if two palms are rubbed together long enough they will start to experience wear). It is the level to which each appears that affects how to approach using certain cutting tools on certain workpiece materials. Friction and abrasion can be increased or reduced by changing either the workpiece or cutting tool material.

Another consideration is how easily the cutting edge of the tool can engage with and cut the material. Cutting tools place a large amount of force on a material in a very concentrated area. If the material in question is one designed specifically to endure high stress, then the cutting process could become incredibly difficult. Machining involves using a very thin cutting edge to compress the material so much that it permanently distorts and breaks. The cutting tool contains spiralled 'flutes' that then force this severed material up and out of the cutting zone. The **hardness** of a material gives an indication of how able it is to withstand any compressive forces acting upon it. The harder something is, the more effort required in distorting it a certain distance.

Figure 1 - An image of an end mill showing eight cutting edges and flutes (Schwarzenberger, 2014)

After a material is released from its compression it will either return to its original shape (reacting elastically) or remain in its compressed form (named 'plastic deformation'). If a material changes shape through plastic deformation, there is a limit to the amount it can change shape before it breaks. The property that governs this is **ductility**. Heated clay is extremely brittle and thus has low ductility, whereas unheated clay is incredibly malleable, exhibiting high ductility.

A final important factor is a solid's **strain hardening** ability. Many materials become permanently weaker after they have distorted under a force, while other have a capacity to become stronger.

Surprisingly, Inconel and titanium have a lower hardness than a standard high-grade steel. However, they are widely regarded as being much more difficult to machine. To understand why, more than hardness must be taken into account. The overall machinability of a material is heavily influenced by the five key properties mentioned above:

- Thermal conductivity
- Abrasiveness
- Hardness
- Ductility
- Strain hardening

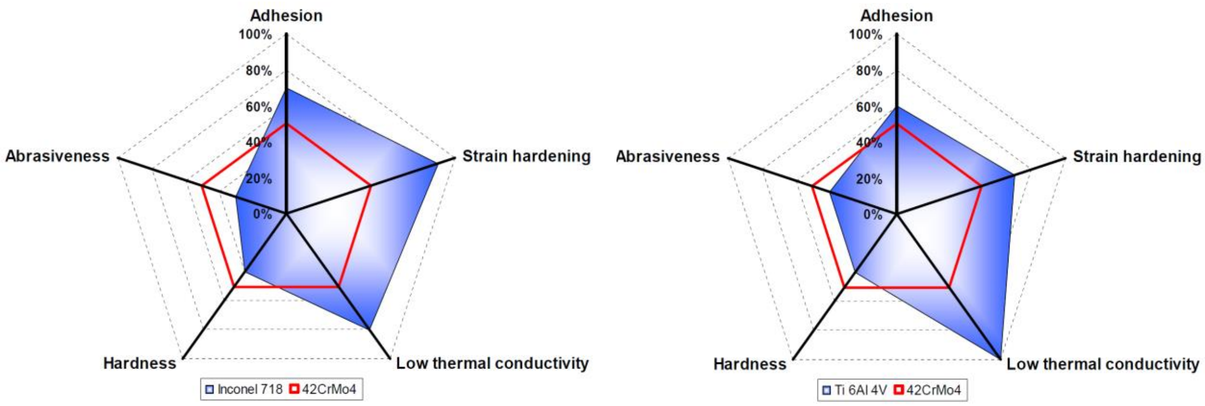

Figure 2 - Graphs showing the five key machinability properties of steel, Inconel and Ti-64 (Seco Tools, 2017)

Inconel and titanium have high levels of strain hardening and low thermal conductivity on top of their lower hardness. Because of this, they need to be machined using an entirely different approach to that of steel. Ignorance of this is what can cause them to be difficult to machine. One of the easiest ways to deal with a difficult material can be to simply lower the feed rate (the linear velocity at which the tool moves through the material), reducing the depth of each cut. Thus, the work applied by the tool decreases and the effects of friction are also reduced due to each tooth on the tool being in contact with the workpiece for a shorter period of time.

Unfortunately, in addition to material considerations another driving factor is production time. If the feed rate is reduced enough to lower the frictional and cutting forces significantly, the duration of the cutting process will sky-rocket. Therefore, there exists a delicate equilibrium between each approach – something which can only really be defined through a large amount of iterative testing. Fortunately, in many cases these tests have already been completed and a number of resources are available to aid with the best approach to machining certain materials. The majority of these resources are publicly accessible, or can be obtained by speaking to cutting tool manufacturers.

Tool Selection

Many issues can also be somewhat alleviated by the use of enhanced tooling. The material of a cutting tool can greatly affect performance. In many machining operations, high-speed steel (HSS) cutting tools are an appropriate choice, being both affordable and effective. The main properties of these steels are high hardness and resistance to abrasion, affording them long lives while reducing the amount of heat generated in the cutting process. However, due to the increased strength of superalloys HSS tools can only be used at incredibly low cutting speeds, less than 5 m/min (M'Saoubi, et al., 2015). This makes them unsuitable for use in production machining of these substances. Utilising cutting inserts (*Figure 3*) made from cemented carbides such as tungsten carbide (Sandvik Coromant, 2017) can have a positive impact on tool wear, but the tool will still struggle at higher speeds due to the forces exacted on its HSS shaft. Even using tools made entirely of carbide can be problematic. These tools struggle with greater abrasive wear during continuous operations, where a large amount of heat will be generated. In addition to the aforementioned effect of heat on the superalloy, the temperature of the metal tool itself will increase, negatively influencing its ability to cut the part.

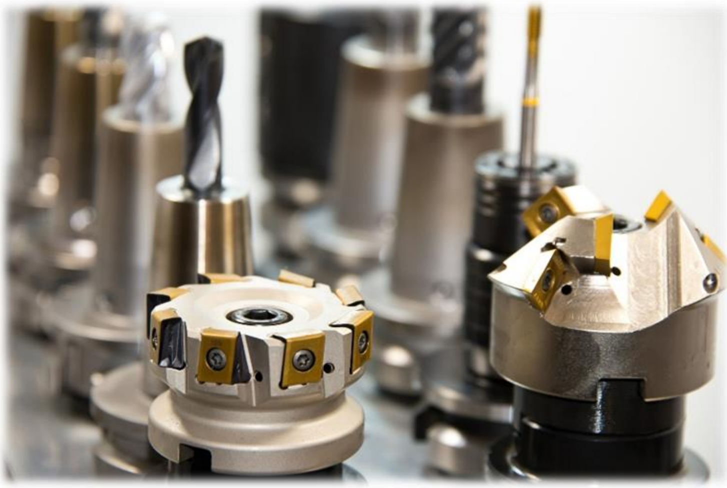

Figure 3 - An image showing two milling tools with inserts (Schwarzenberger, 2014)

Rather than any metallic tools, the employment of ceramic tooling in applications such as this is increasingly common. Unlike metals, ceramics are thermal insulators. This means that they are much less prone to changes in temperature, even in situations where large amounts of abrasion can occur. This helps to keep the tool's performance constant, with the majority of the heat instead transferred to the chips of swarf created by the cutting process. Ceramic tools require very high spindle speeds (within the realm of 40,000 rev/min, unfortunately greater than some machines can handle) and a steady feed rate to work effectively (Koepfer, 1999). The high speeds mean a great deal of heat can be generated. Because of this, one of the main indications of a ceramic tool being used is that any swarf will glow red-hot. It is important to evacuate this material as fast as possible to keep the heat away from the rest of the superalloy. But this cannot be done by the conventional means, which is a steady stream of coolant.

At home in the kitchen, if one were to place a hot plate on a cold surface that plate is likely to smash – or at least crack. This is because most ceramic materials are exceptionally brittle (Whitney, 1994) and so any failure can be catastrophic. Sudden changes in temperature can cause rapid expansion or contraction of the ceramic material and instigate this failure. Whereas metal tools can gradually fail plastically, if a ceramic tool fails the resulting incident could be spectacular. Therefore, it is considered unwise to spray chilled coolant onto a section of a heated ceramic tool. Rather, a jet of air is used to immediately blow away any chips created from machining. Should the need arise, inserts can also be used on ceramic tools, with Polycrystalline Cubic Boron Nitride (PCBN) (CeramTec, 2017) being among the most popular. As a material, PCBN is second only to diamond in terms of hardness and is much more practical and easily-obtainable. In fact, PCBN cutting surfaces are more likely to wear due to chemical interactions between themselves and the part than from abrasion (M'Saoubi, et al., 2015).

The Creation of Superalloys

Another aspect that warrants consideration is that of how the block of material itself was formed. When using superalloys, the general shape of a part is often created through either a forging or casting process. Casting is a process that has been used for over 5000 years, with evidence dating back to 3200BC (Ravi, 2011). The method involves pouring or injecting molten metal into a shaped cavity, before allowing it to solidify. In forging, solid metal is forced into a certain shape. In a similar way to how medieval blacksmiths hammered swords or armour into shape, a modern forging process might use a powered press with a shaped die on the end to obtain a desired part. Forging can be accomplished using hot or cold metal, with the processes referred to as hot forging and cold forging accordingly.

Figure 4 - Molten metal being poured into a cast (Arango, 2016)

Each forming process has significant advantages and disadvantages, leading to why one might be used over the other. Subsequently, whether a part was forged or cast also influences how one might approach machining it. Superalloys are made of a series of metallic crystals (Reed, 2006) and it is the interlocking arrangement of this crystal structure that makes them so strong. Generally, when a material such as this is created, the alignment of the crystals is controlled in order to maximise the desired properties. It is also possible to create superalloys that consist of just a single crystal. However, these are much rarer and will not be discussed here.

Figure 5 - A worker operating a manual forging machine (Hine, 1937)

Through the process of melting the metal alloy for casting and re-solidifying it, the physical make-up of the material is altered. The regular structure can become erratic, slightly weakening the whole material and making it easier to machine. However, a possible result of casting can be a 'skin' on the surface of the material, an oxidised layer. This can cause a great deal of tool wear so caution is advised, but once it is removed machining can continue as normal. Conversely, in forging the alloy remains a solid, so the integrity of the material is preserved. However, as cold forging is essentially just a bending of the part, additional stresses are introduced. This should not drastically affect the way in which the part would be machined, but it is worth noting. Hot forging alleviates this somewhat by granting the crystals more of an ability to shift position (Higgins, 2006). This is not the same as the reforming that occurs during casting, but the internal structure adjusts itself slightly to the new shape. Hot forging, like casting, can cause a scale to form on the material exterior, where the metal has reacted with the oxygen in the air. Steps can be taken to prevent this, but when machining it is important to cut this layer using a shallow cutting depth so as to minimise excessive force on the cutting tool.

Machining Trials

Description of Tests

In 2017, cutting tests were carried out in Autodesk's Advanced Manufacturing Facility (AMF) in Birmingham, UK. The recently-renovated AMF covers an area of 12000 sq ft, containing 20 machines capable of dealing with a wide variety of manufacturing tasks, from applying additive techniques like Wire Arc Additive Manufacturing (WAAM) and laser-based Directed Energy Deposition (DED) to simultaneous 5-axis milling and turning.

The aim of these tests was to assess various approaches to cutting Inconel-718, Ti-6Al-4V and EN24T steel. Two manufacturing programs were prepared for the three blocks, each to cut an open slot of dimensions 25mm x 100mm x 18mm. Of these two programs, one utilised settings that might be used for cutting a medium-grade steel (such as the EN24T used in the experiment) and the other had settings that are more ideal for cutting the material in question. The programs were run on a Huron VX12 3-Axis CNC milling tool (*Figure 6*), with a new 4-flute, 12mm end-mill with a 1mm tip-radius tool (supplied by SGS tooling) used for each cut. The tools were all made of Z-Carb carbide, designed to cut a range of material groups with differing hardnesses and machining characteristics.

Figure 6 - An image of a Huron VX12

As mentioned in a previous section, most tooling manufacturers have documents available to the public which show the different speed and feed recommendations for cutting certain materials. The values obtained directly from SGS Tools were used throughout the trials (*Figure 7*). In addition to these changes in speeds and feeds, the toolpaths themselves were altered to suit each cutting method. The full list of machining parameters can be seen in Table 1. An image of each toolpath is shown in Figure 8.

Series Z1M, Z1MB Metric	Hardness BRINELL		Ae x D_1	Ap x D_1	Vc (m/min)	Diameter (D_1) (mm)	3	6	8	10	12	16	20	25
P – CARBON STEELS 1018, 1040, 1080, 1090, 10L50, 1140, 1212, 12L15, 1525, 1536	≤ 275	Profile	≤ 0.5	≤ 1.5	169	RPM	17934	8967	6725	5380	4484	3363	2690	2152
					(135-203)	Fz	0.009	0.024	0.041	0.051	0.060	0.079	0.086	0.088
						Feed (mm/min)	654	861	1091	1090	1076	1067	927	753
		Slot	1	≤ 1	134	RPM	14218	7109	5332	4265	3555	2666	2133	1706
					(107-161)	Fz	0.009	0.024	0.041	0.051	0.060	0.079	0.086	0.088
						Feed (mm/min)	519	682	865	864	853	846	735	597

Series Z1M, Z1MB Metric	Hardness BRINELL		Ae x D_1	Ap x D_1	Vc (m/min)	Diameter (D_1) (mm)	3	6	8	10	12	16	20	25
S – SUPER ALLOYS (NICKEL, COBALT, IRON BASE) Inconel 718, 750X, Incoly 925, Waspaloy, Hastelloy, Rene	> 300	Profile	≤ 0.5	≤ 1.5	19	RPM	2003	1002	751	601	501	376	301	240
					(15-23)	Fz	0.002	0.007	0.011	0.013	0.017	0.020	0.024	0.025
						Feed (mm/min)	19	29	32	32	34	31	29	24
		Slot	1	≤ 1	15	RPM	1583	792	594	475	396	297	238	190
					(12-18)	Fz	0.002	0.007	0.011	0.013	0.017	0.020	0.024	0.025
						Feed (mm/min)	15	23	25	25	27	24	23	19

Series Z1M, Z1MB Metric	Hardness BRINELL		Ae x D_1	Ap x D_1	Vc (m/min)	Diameter (D_1) (mm)	3	6	8	10	12	16	20	25
S – TITANIUM ALLOYS Pure Ttanium, Ti6Al4V, Ti6Al2Sn4Zr2Mo, Ti4Al4Mo2Sn0.5Si	≤ 350	Profile	≤ 0.5	≤ 1.5	66	RPM	6947	3474	2605	2084	1737	1303	1042	834
					(52-79)	Fz	0.005	0.012	0.021	0.027	0.031	0.041	0.045	0.045
						Feed (mm/min)	133	167	222	222	217	213	189	150
		Slot	1	≤ 1	52	RPM	5493	2747	2060	1648	1373	1030	824	659
					(41-62)	Fz	0.005	0.012	0.021	0.027	0.031	0.041	0.045	0.045
						Feed (mm/min)	105	132	176	176	171	169	149	119

Figure 7 - Machining recommendations for cutting operations with carbon steels and Inconel (SGS Tools, 2015)

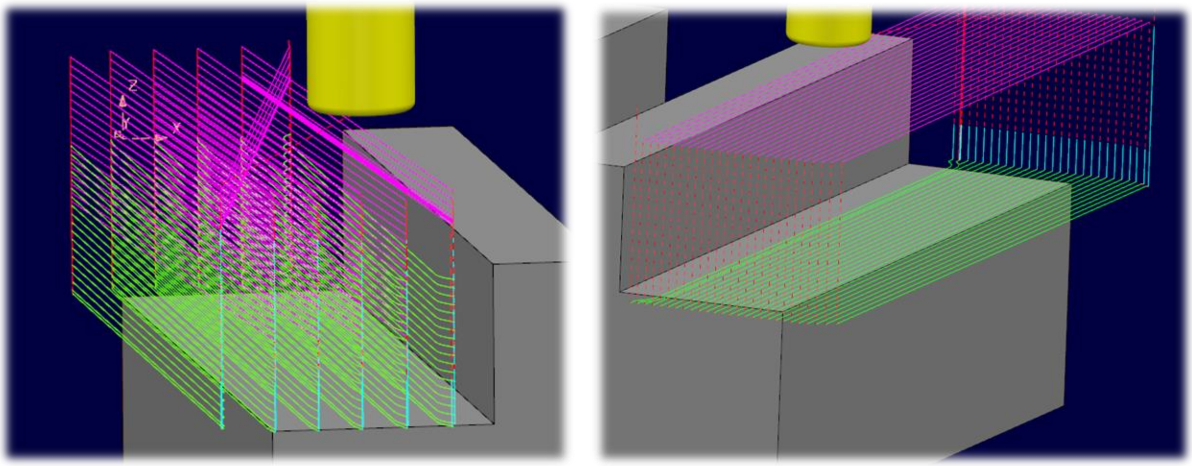

Figure 8 - Images showing the toolpaths as prepared for steel (left) and Inconel (right)

Parameter	Steel	Inconel	Titanium
Stepover (mm)	4.8	1.2	1.2
Stepover (% of Tool Diameter)	40	10	10
Stepdown (mm)	1	18	18
Stepdown (% of Tool Diameter)	8.3 (Tip Rad. size)	150	50
Feed Rate (mm/min)	1076	34	217
Spindle Speed (rpm)	4484.0	501	1737
Approx. Machining Time	20 minutes	1 hr 50 minutes	16 minutes

Table 1 - A list of settings that were used for each toolpath

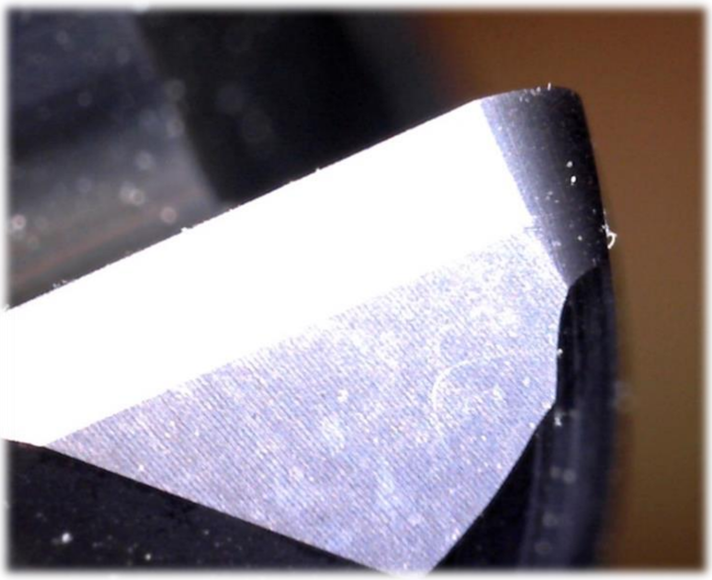

Figure 9 – An image of the cutting edge of a Z-Carb end mill before it has been used to cut any material

Using a microscope, photographs were taken of the tooling before and after the trials had taken place, to show the different effects the cutting parameters had. The initial state of the tool cutting edge can be observed in Figure 9. Note how defined the cutting edge is.

Cutting Inconel-718

On the other hand, Figure 10 shows the tools cutting edges after the first machining trial using medium-grade steel feeds, speeds and approach on Inconel-718. These images highlight the importance of a completely different approach to machining when working with materials such as Inconel-718. With the settings as they are for medium-grade steel, the cutting forces are localised to the cutting tip. However, because of the high strain-hardening capacity of Inconel-718, this has a drastically negative effect on the cutting tool. After only four passes at the first depth of cut, the cutter could not continue.

Figure 10 - The cutting edge of a Z-Carb tool after it has been used to cut Inconel-718 with steel settings

As well as damage to the tool, the surface quality of the material was affected by using medium-grade steel parameters. The two pictures in Figure 11 show the surface after it has been machined. The left-hand image shows chattering, caused when the tool is unable to remove the material at the rate required, thus causing excessive vibrations. The right-hand photograph shows changes in colour, which would usually be caused by excessive heat in the material. In this case, because of the inherent properties of Inconel-718 this heat would cause the material to strengthen, further exacerbating the problem of chattering.

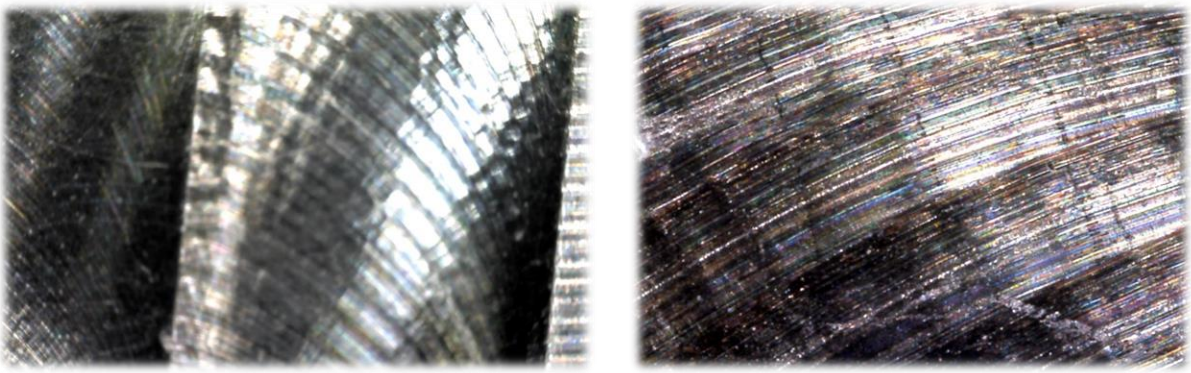

Figure 11 - Images of the surface of Inconel-718 after it has been cut using medium-grade steel methods

Following this, toolpaths with the appropriate feeds, speeds and approach for Inconel-718 were used. Figure 12 shows the tool wear after the area was machined. As can be seen, when machining the material with correct parameters there is a lot less wear and the wear that is apparent is also a lot more uniform. The deeper step-down meant the heat and cutting forces were spread over a larger area (along the flute of the cutter). This, on top of slowing down the speeds and feeds to reduce overall force, enabled the complete machining of the area. The one downside is that the reduced feed rate meant this procedure took over five times as long as the full cut using carbon steel parameters. However, the fact that the tool is serviceable for more than four passes makes this method seem much more favourable. Looking at these results and assuming no further machining needs to be completed, there is enough leeway for the spindle speed and feed rate to be increased slightly with the intention of reducing cycle time.

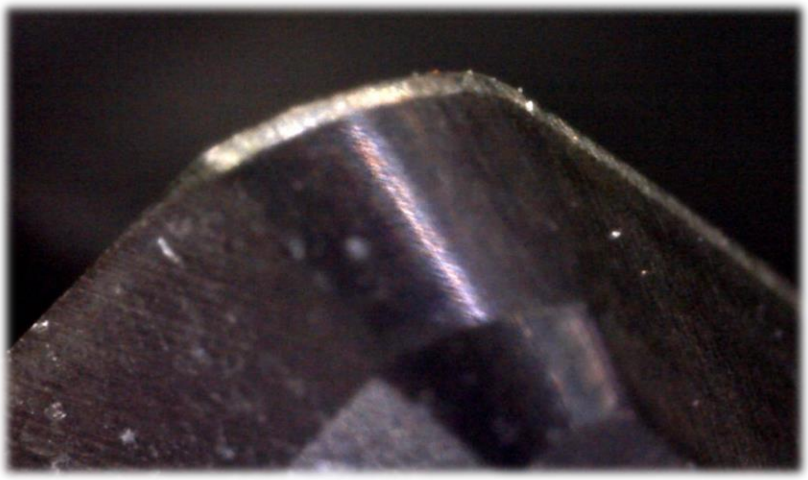

Figure 12 - The cutting edge of a Z-Carb tool after it has been used to cut Inconel-718 with Inconel settings

Using the correct parameters also meant the surface finish of the material improved. As is shown in Figure 13, the effects of chatter and heat change have been reduced presumably due primarily to the lower speed and smaller stepover.

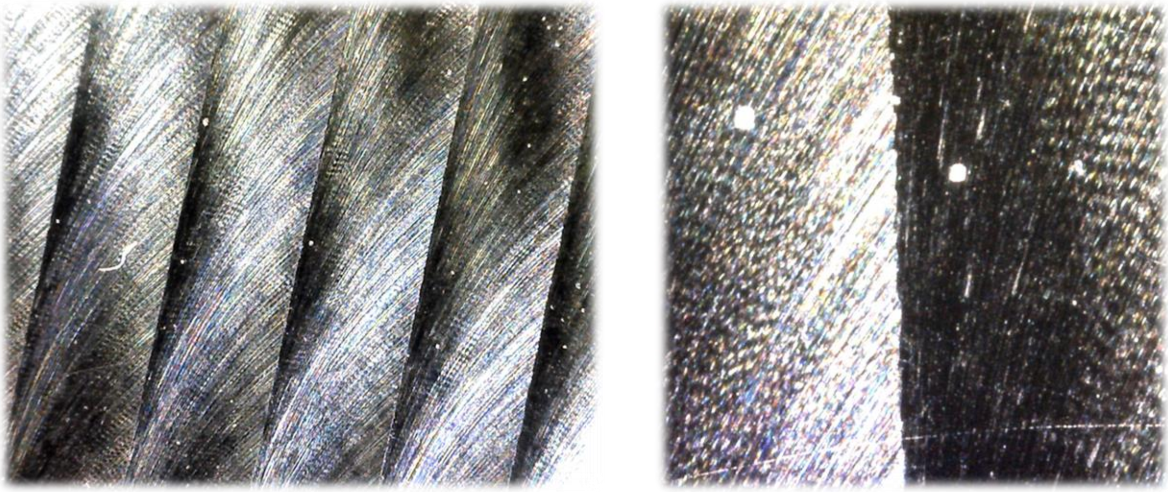

Figure 13 - Images of the surface of Inconel-718 after it has been cut using Inconel methods

Cutting Ti-6Al-4V

Ti-6Al-4V (or Ti-64 as it is commonly known) was the next material to be tested. The assessment procedure was almost exactly the same, apart from the second slot using the settings for Titanium displayed in Table 1. The technique for cutting steel was applied to the Ti-64 block first. This time, the tool managed 60% of the area before it could no longer cut effectively. Figure 14 shows a chipped corner and worn cutting edge of the tool after this first toolpath was stopped.

Again, the quality of the machined surface also suffered. Although there was no discolouration due to high temperatures or excessive chattering to the extent seen with Inconel, other issues were found. Most likely due to the cutter being unable to remove the material at the required rate, some of the swarf has welded itself back to the workpiece (*Figure 15*). This would be due to the cutter pushing, rather than cutting, the material.

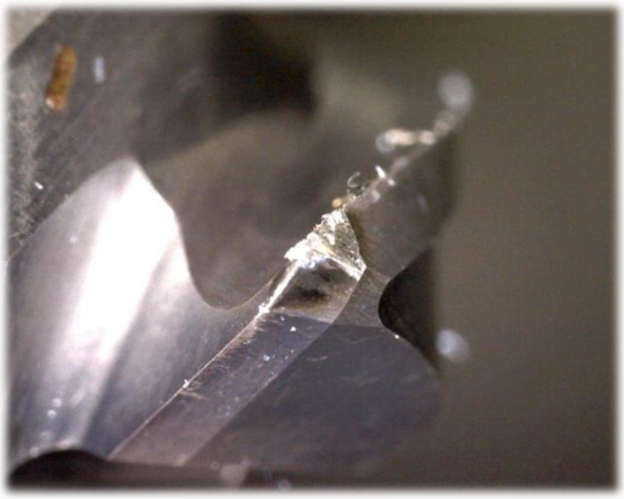

Figure 14 - The cutting edge of a Z-Carb tool after it has been used to cut Ti-64 with steel settings

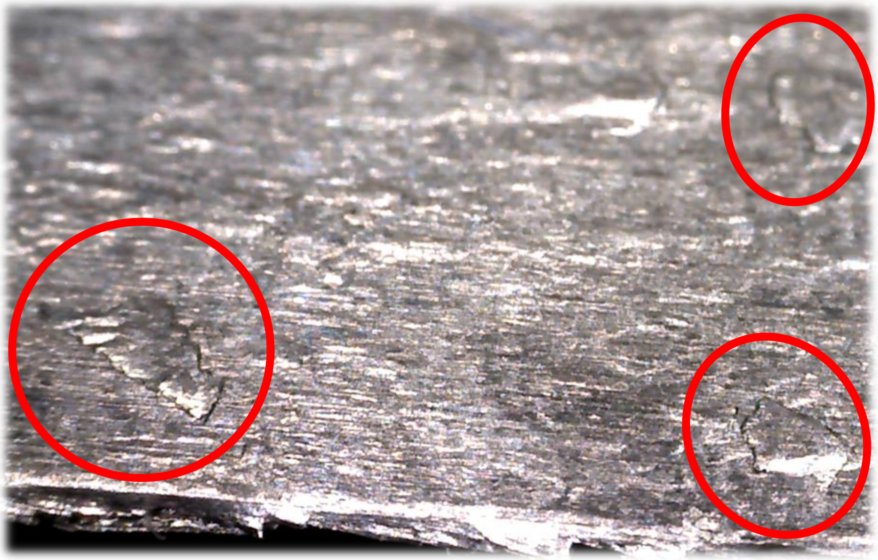

Figure 15 - An image of the surface of Ti-64 after it has been cut using medium-grade steel methods

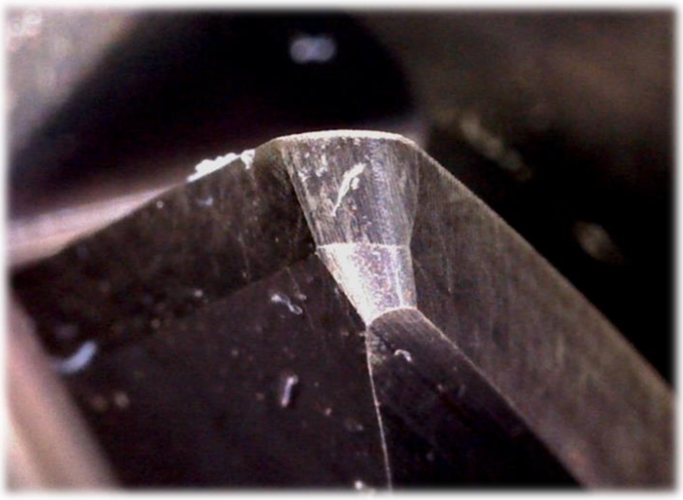

Figure 16 - The cutting edge of a Z-Carb tool after it has been used to cut Ti-64 with titanium settings

When cutting with the correct conditions, the entire volume was able to be completed. The cutting surface of the tool was much more reasonable (*Figure 16*) and all instances of the swarf welding to the surface had been removed (*Figure 17*). The cycle time of the second toolpath was actually lower than that of the steel-based one, meaning not only are there obvious advantages in terms of results but there will be greater cost-reducing benefits.

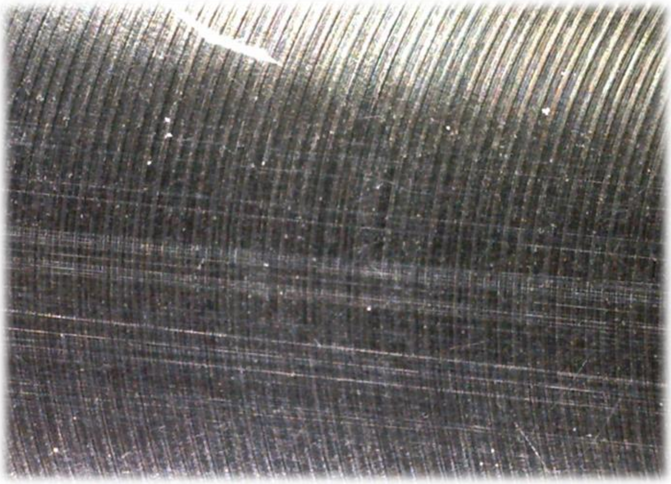

Figure 17 - An image of the surface of Ti-64 after it has been cut using titanium methods

Cutting EN24T Steel

Unlike the previous two trials, for steel the ideal cutting conditions are those for the initial toolpath. Therefore, this assessment served as a sort of 'control' result, a point of comparison from which to compare the other results. The results of this toolpath show that the initial settings can produce good results, given the correct material.

After machining the volume, the cutting edge of the tool displayed only slight wear (*Figure 18*). Upon closer inspection, the main form of ears seems to be from heat build-up at the cutting edge, which could be further negated by spreading the load over a greater length of the tool's flank (*Figure 19*). Figure 20 shows the machined surface, with no signs of heat distortion or chatter. These results seems to suggest the toolpath and settings are appropriate for cutting a material such as this.

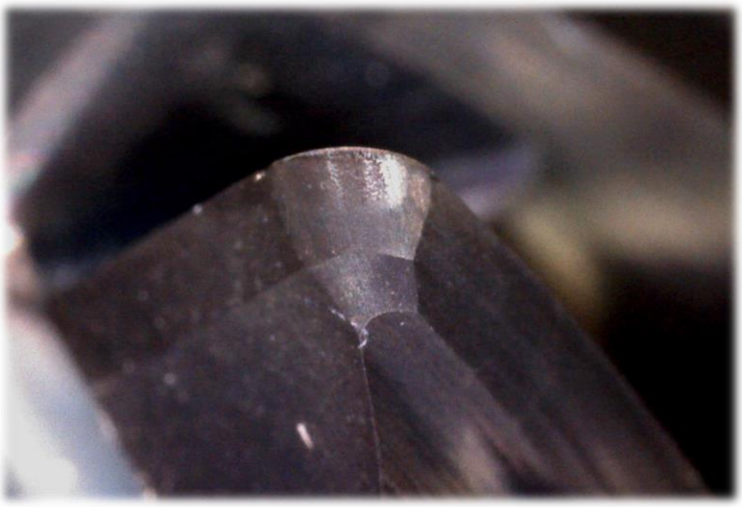

Figure 18 - The cutting edge of a Z-Carb tool after it has been used to cut EN24T steel with steel settings

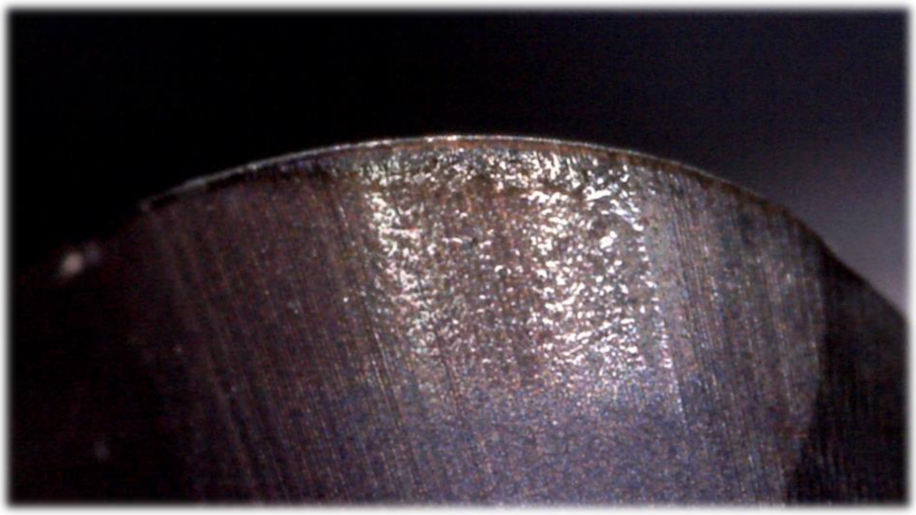

Figure 19 - A zoomed view of the cutting edge in Figure 18

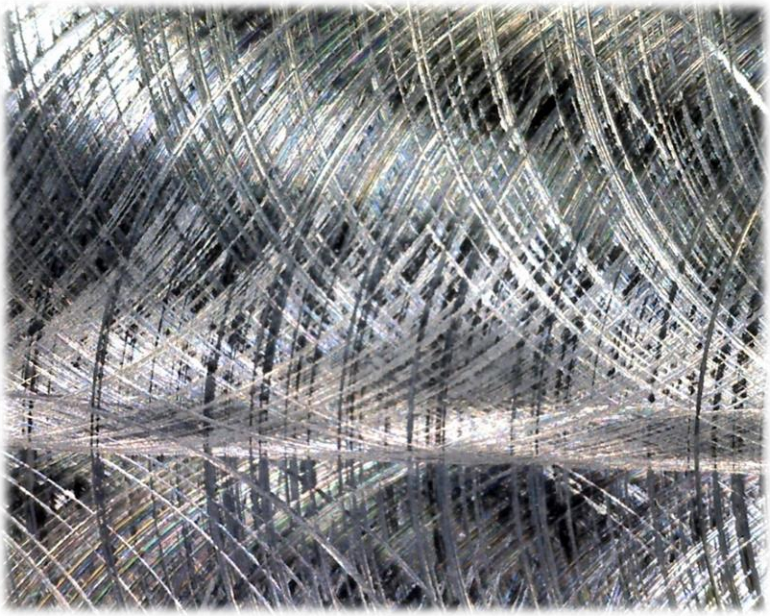

Figure 20 - An image of the surface of EN24T after it has been cut using medium-grade steel methods

Industrial Case Study 1

Rolls-Royce Trent Engines

Rolls-Royce is a familiar name worldwide and has been for decades, known mostly for their luxury motor cars and aero engines, despite also being heavily involved in the marine and energy generation industries. However, in 1971 the Rolls-Royce business entered financial difficulties. This led to a split of its products, with BMW currently holding ownership over the car brand. Conversely, its aero engines are now produced by the public-owned company Rolls-Royce Holdings plc. This has had a majorly positive effect on revenue, with Rolls-Royce predicted to be the third largest manufacturer (The Statistics Portal, 2017) of commercial aircraft engines in 2016.

A primary reason for this is the success of the Rolls-Royce Trent series, used as part of many airliners – from the Airbus A330 in (Rolls-Royce plc., 2017) 1995 to the more modern Boeing 787 Dreamliner (Rolls-Royce plc., 2007). Designs in the Trent family are all high bypass turbofan engines, using a three-spool setup rather than the more common twin-spool configuration. A turbofan is a jet engine, burning fuel in a turbine in order to power a cylindrical spool (also referred to as a shaft) running through its centre. This spool is used to turn an array of fan blades, pushing air out of the rear of the engine and providing thrust. In a turbofan engine, only a portion of the air taken in is used in the turbine itself, the rest passing solely through the fan. Thus, a high bypass engine is one where a high proportion of air 'bypasses' the turbine in this way. Two-spool engines have the fan and turbine mounted on separate but connected shafts, allowing them to rotate at different speeds. The Rolls-Royce Trent three-spool design utilises an additional turbine mounted on its own shaft, allowing the fan to operate at a slower speed.

Advancing the Trent Design

The first of Rolls-Royce's Trent engines became commercially available in 1990. Since then, there have been a number of variants of the original concept – some being modifications to adapt the engine for certain aircraft, others with the aim of slightly improving efficiency. However, in 2014, Rolls-Royce announced an intention to overhaul the design of the Trent engines (Norris, 2014). The project is split into two stages, Advance and UltraFan. The Advance itself is not scheduled for commercial release, instead serving as a transition between previous Trent designs and the new UltraFan, which it is said could lead to a 25% improvement in efficiency.

Advance3 Blisk Project

In February of 2014, AAC was approached to produce two copies of a blisk from the intermediate compressor of the Advance3 demonstrator engine. A blisk is simply a combination of the words blade and disk, used to describe a part where both are manufactured as a single solid item. Advance3 is the name given to one of the physical engines created from the Advance design. The blisk was to be machined from a solid cylindrical forging. The cylinder consisted of hot-forged Titanium-64 and contained an axial hole in its centre. The part was provided as a bright forging, with all of the hardened 'black' material removed by the customer. All manufacturing was done at the Advanced Manufacturing Facility in Birmingham, UK on a Hermle C50.

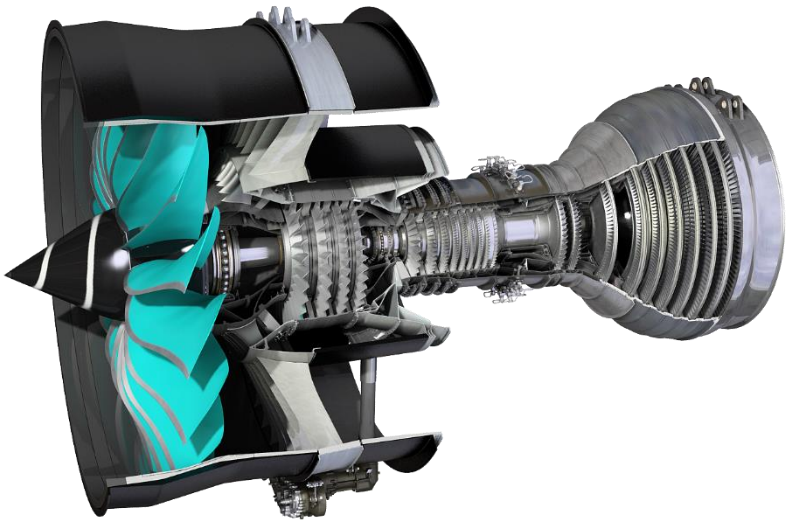

Figure 21 - An image of the Rolls-Royce Advance engine concept (Rolls-Royce plc, 2016)

Figure 22 - An image of the bright forging received from Rolls-Royce

Before any machining could be completed, a fixture needed to be designed to secure the part for machining. Prior to doing this, it can be a good idea to completely storyboard the machining that will be undertaken. The fixture needs to clamp the part enough to resist all cutting forces, so those forces must be determined. However, if the clamps are too forceful the part can distort under their pressure, perhaps causing a redesign of the fixture or the manufacturing process.

To test the fixture and the cutting sequence, a full test piece was made from steel before machining the two Ti-64 blisks. Additionally, a series of blade samples (blocks of 4-5 blades) were created to check that the requested surface finish was obtainable. Using dummy parts in this way allowed different techniques and parameters to be tested without ruining the actual parts.

The process of cutting the blisk was broken down into five stages:

1. Roughing side 1
2. Roughing side 2
3. Fully milling the blades
4. Finishing side 1
5. Finishing side 2

Roughing is a cutting process created with the intention of removing excess material as quickly as possible. After roughing, a small material thickness is left on the part and, as such, surface finish and tolerance are less of a concern. Semi-finishing and finishing toolpaths are generally conducted at slower feed rates and at a lower depth of cut in order to ensure they produce smooth and accurate results. In semi-finishing a tiny thickness (no less than 0.2mm) is left on the material, with true finishing cuts used to machine to the designed depth.

The two roughing processes consisted of turning the forging into the correct shape to minimise the amount of material that had to be milled when cutting the blades. As opposed to milling, which involves rapidly spinning a tool and manoeuvring it such that it cuts into a part, turning involves instead rotating the part and using a fixed tool. The tool can then be translated in the X, Y or Z axis to engage with the part and allow certain designs to be cut. The process can be imagined as similar to a vase being shaped on a spinning pottery wheel. Cylindrical parts lend themselves well to this technique, able to cater for an even depth of cut around their entirety – although it is also possible to cut non-circular shapes in this way.

After turn-roughing the first side, a linear notch was cut into a designated mating face (*Figure 25*). This cut was made to allow the part's radial position to be accurate and repeatable. The technical term for a slot with this purpose is a mortise. The fixture had also been created with a clamp of similar dimensions – called a tenon – to snugly fit into this slot. In order to machine both sides of the part, it had to be removed from the fixture and carefully flipped. When placed back on the fixture the tenons and mortises were matched up. This helped to machine an identical slot on the reverse side after it too had been turn-roughed.

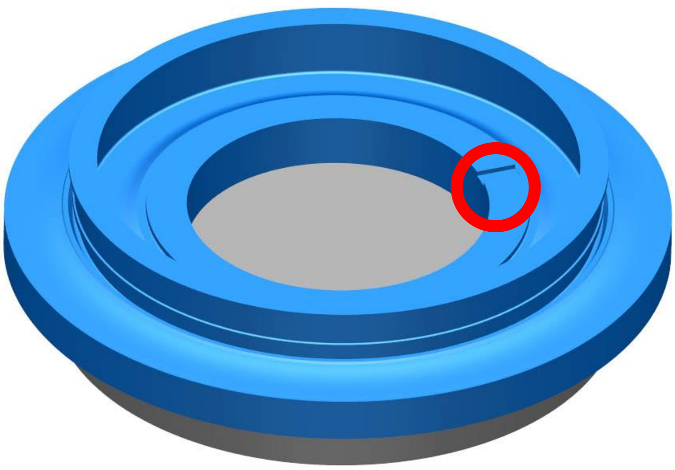

Figure 23 - An CAD model of a mortise cut into the stock after it has been roughed

Even the act of flipping the cylinder can be a difficult task. The considerable weight needs to be lifted securely, without any possible damage to the part. A common way of securing a part throughout this process is by simply placing it in a cushioned or specially-shaped box. When designed correctly, the box supports the part sufficiently enough to prevent it from moving and damaging itself, as well as providing easy attachment points for the device used to flip it. For this project, the cylinder was slotted onto a central wooden hub in a cuboid box and flipped by a crane (*Figure 24*).

Figure 24 - A photograph of the Advance3 blisk in its flipping box. An identical piece was used as the lid

After the first two rough-turning stages had been completed, the blades were completely milled – roughing, semi-finishing and finishing. Within a cylindrical solid there can be a large amount of tensile stress, especially if that solid has undergone a forging process. This is named hoop stress and is distributed regularly throughout the shape. In order to create blades, slots need to be cut in the outer diameter of the cylinder. Doing so releases some of the hoop stress and redistributes the rest. The tensile forces in the material pull against the sides of the slot, widening and distorting it since the tensile force pulling in the opposite direction has been cut away. If a blisk's blades are cut in sequence, there will continuously be a strong tensile force from the large volume of material in the uncut sector of the cylinder. This makes each slot slightly wider than it should be and weakens the material by also causing an uneven distribution of stress. This can be relieved by cutting in such a way as to produce similarly-sized sectors. For example, cutting at 0° and then at 180° will cut the perimeter into two arcs of equal length. Cutting again at 90° and 270° will then produce quadrants and four more cuts can be made to halve each of those, et cetera (*Figure 25*). Even if these exact angles cannot be used, following this concept whenever cutting into a cylinder will preserve the strength of the material and ensure the slot sizes are as accurate as possible.

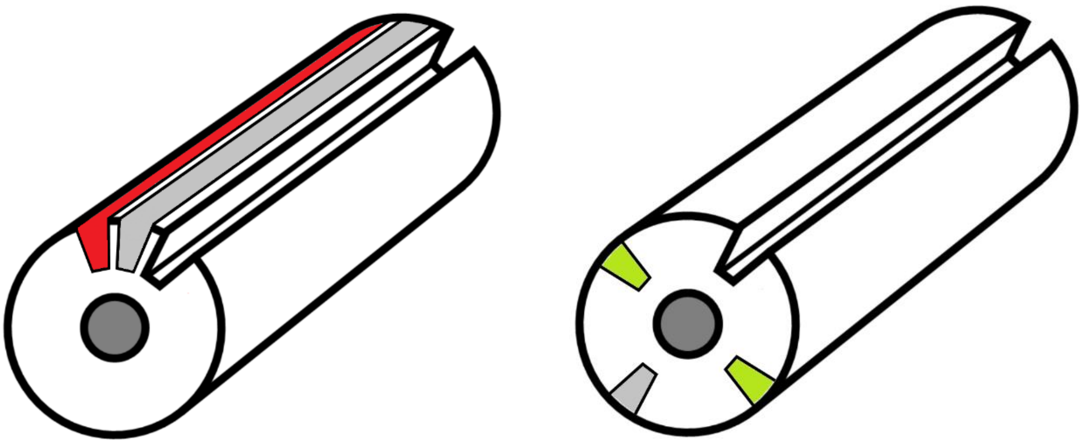

Figure 25 - Images showing a non-ideal method (left) and ideal method (right) for cutting slots into a cylinder

Figure 26 - An image of slots being cut into the outside of the blisk in such a way as to regulate hoop stress

Once the slots between each blade were created, the shape of each blade was roughed. The blades in this design were long and thin, meaning that a small amount of force at their tip could cause them to bend out of shape, reducing machining accuracy as a result. Furthermore, the forces from machining could cause them to vibrate, causing a rough surface finish from an effect named 'chattering'. Refraining from machining certain areas of the blade until it is absolutely necessary helps to provide the thinner sections more support and stability. In this project, the length of each blade was separated into three – top, centre and bottom. First, every blade in the blisk was roughed in its entirety. After this, the remaining processes made use of the three blade sections. The top of each blade was semi-finished and finished as a single operation. This meant the lower, unmachined portions of the blade formed what is called a 'monolith', a thick chunk which served to give strength to the slimmer part above it during machining. Repeating this process for the length of the blades helped to minimise the amount of chatter experienced.

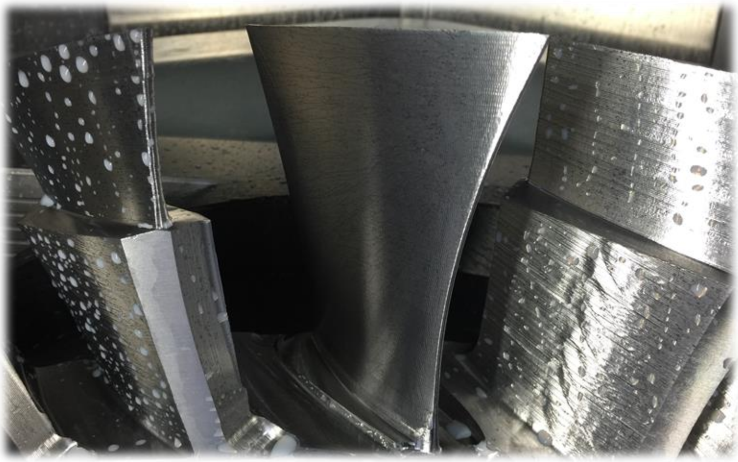

Figure 27 - An image showing a fully-machined blade with monoliths on either side

After completing the final two turning processes, the part then had to be:

1. Inspected, to ensure it had been machined accurately
2. Polished, to create the smooth surface finish required
3. Tested, to ensure it would operate as desired polished
4. Packed, ready for a safe return to the customer.

Industrial Case Study 2

Adaptive Repair Processes

Parts used in the aerospace industry generally have a very strict lifespan. Because there is an emphasis on efficient performance and safety, once a section of aircraft/spacecraft reaches a certain level of use it is immediately replaced. Therefore, supplies of new parts are regularly required. Machining these parts from scratch is not the only way meet this demand. Starting anew each time is cost- and time-consuming, with numerous processes involved and a large amount of waste material. Often, it is much more economical to restore existing parts that might have been retired due to damage or fatigue, since they are already the correct shape. In situations such as this, it is common that only certain areas of the geometry need be repaired or strengthened.

One example of the use of adaptive repair in industry is in the repair of turbine blade tips. In an engine, the ends of the rotating blades can get worn down through friction or damaged by dust. Since each blade is specifically designed with maximising fuel efficiency in mind, chips and scratches on the surface can be detrimental. Since most of the damage is likely to be at the tip, welding some additional metal to the end and machining the excess away is a simple way of restoring the blade. However, one difficulty in using this method is that each blade is likely to have been distorted slightly through use. Should this distortion be deemed acceptable, any re-machining needs to take it into account. Identical processes cannot be used for each repair, as what might machine one blade correctly could gouge or crash into another if there is even a slight difference in geometry.

Therefore, cutting programs must adapt to each new model to ensure this doesn't happen. This involves carrying out new design steps for each blade, with the aim of defining the exact path that the cutting tool needs to take. And this concept does not apply to solely the aerospace industry. For example, some additive manufacturing processes make use of supports – sections which help the model to be constructed but which are not intended as part of the design, as can be seen in *Figure 28*. These supports would need to be removed from the main design and one method of doing so is by machining them away. An adaptive system would recognise the location of these supports and capture the geometry of the main design, using them both to create a series of toolpaths.

Figure 28 - A 3D printed part (black) with overhanging areas supported by additional material (white). This part was produced by the Advanced Manufacturing Facility of Autodesk (Birmingham, UK)

Outlet Guide Vane Project

Within an aircraft engine, there are many other elements than turbines and fans. Outlet Guide Vanes (OGVs) are aerofoil-shaped structural supports used to guide air from the fan to the back of the engine. These are fixed components, i.e. they do not move as the engine shaft rotates.

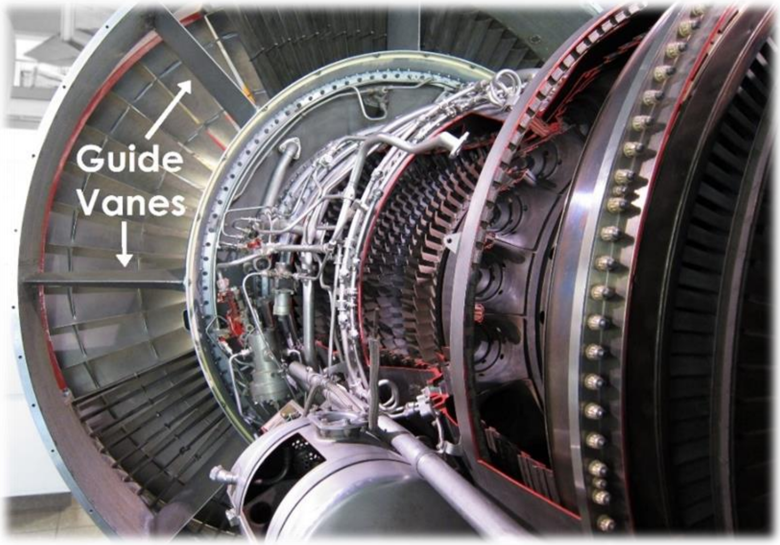

Figure 29 - An example of guide vanes as part of a Pratt & Whitney JTD9-D7 engine (Cleynen, 2011)

In 2006, AAC started work on creating a system used for adaptively trimming three variants of OGV for each of the Rolls-Royce 1000, XWB, 900 and 700 Trent engines – 12 possible different designs in total. The system would eventually automate the production of every part, able to recognise each individual variant and generate inspection routines and toolpaths accordingly. These OGVs were made from Titanium-64 via a superplastic forming process. Superplastic forming is similar to hot forging in that the material is heated and forced into shape after being exposed to a large amount of pressure. However, in this instance the pressure is from gas injected inside the material, expanding it like a balloon. This method is an effective way of producing hollow shapes without introducing additional stresses.

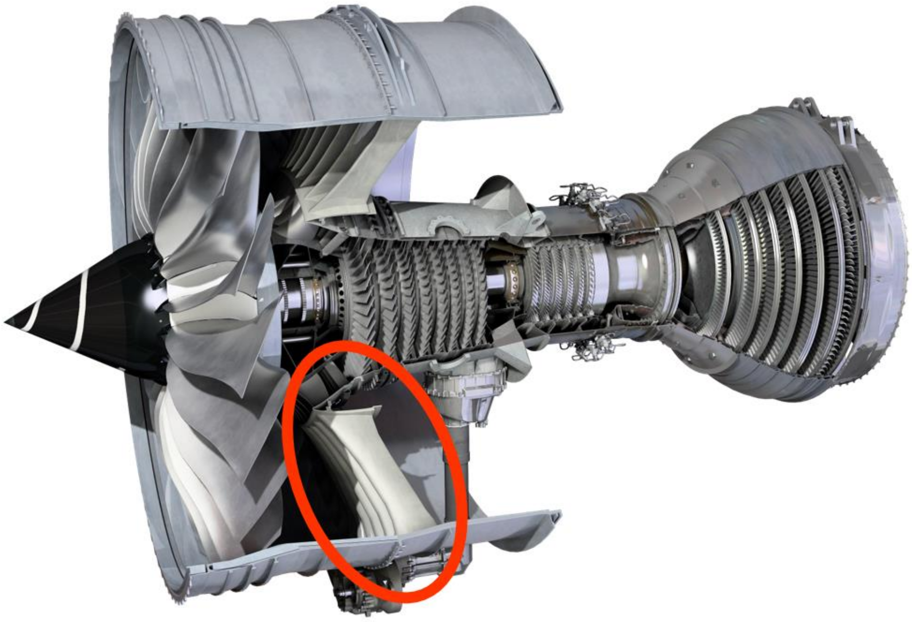

Figure 30 - An image of the OGV machined in this project as part of a Trent 100 engine

The task for each OGV was to machine the leading edge of the vane into an elliptical shape to allow it to cut more easily into the airflow, minimising drag. Under standard conditions this would have been an easy task, simply producing twelve programs – one for each variant. However, superplastic forming is not the most accurate method of shaping parts. Therefore, the exact geometry of each iteration was likely to vary, from one to the next. This means that using identical toolpaths for each job was ill-advised as they would not be accurate to every part. The solution was to create an adaptive process, allowing each toolpath to be morphed with the intention of producing a smooth blend between the machined and stock surfaces (*Figure 31*).

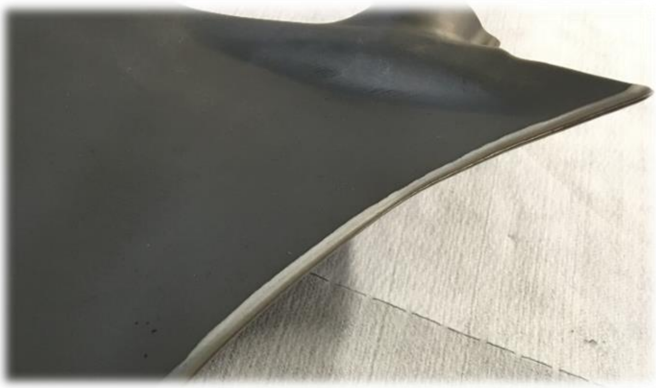

Figure 31 - An example of the desired blend between the machined edge and the existing surface

In order to implement this adaptive process and produce the correct shape, the first task was to probe the OGV once it had been loaded into the fixture on the machine tool. Because the part was hollow and relatively thin, clamping the part to this fixture would have distorted it, perhaps even plastically. Therefore the fixture utilised a vacuum-based system, with the part located using pins and then fixed in place using a strong suction force.

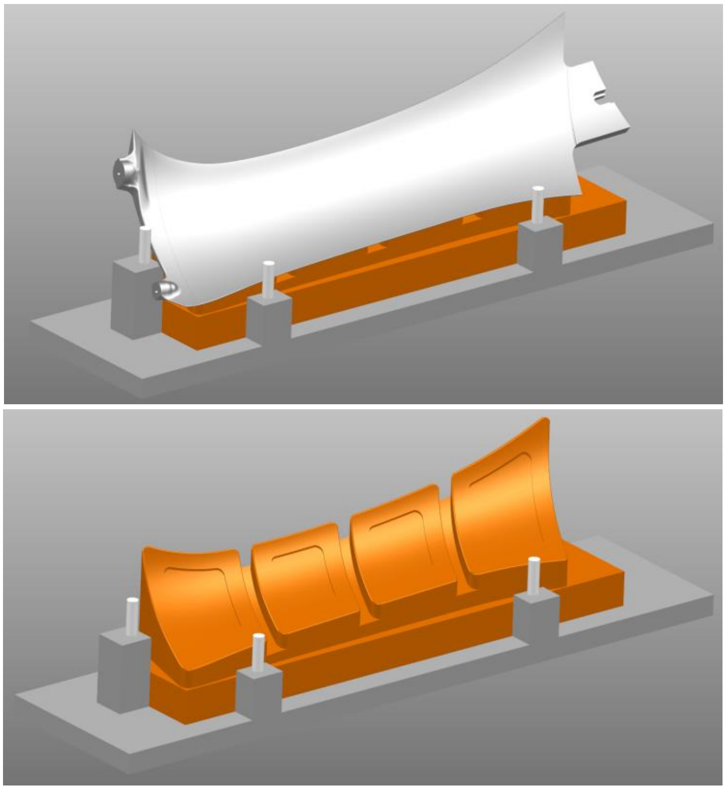

Figure 32 - An image of the OGV vacuum fixture with (above) and without (below) the part loaded.

A series of initial inspection routines allowed the alignment of the OGV to be established, important for producing accurate results. If the virtual and physical positions of the part are different, any cutting processes would include an unwanted offset or rotation. After alignment, more probing sequences captured the geometry of the OGV tip. The precise co-ordinates of each point were combined within the Autodesk PowerShape CAD software to construct a surface defining the existing OGV shape. A second elliptical surface was then created from the internal lateral curves of the first. It is important to use at least 2-3 of the curves from the original surface to ensure the blend after machining does not contain any steps or sharp angles.

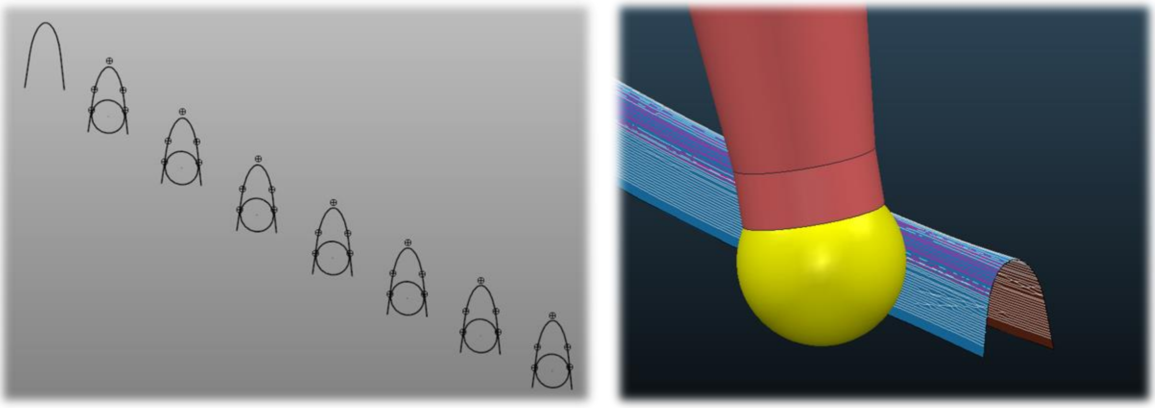

Figure 33 - Images showing curves that lead to the creation of an adapted cutting surface in PowerShape (left) and a simulation of that surface being cut in PowerMill (right)

The second surface was imported into Autodesk PowerMill for CAM work. The adaptive system utilised pre-made toolpath templates, recalculating them for each new piece of geometry. This cut out unnecessary setup time and meant the entire CAD/CAM process could be automated, running without any user input or guidance.

Cutting the OGV was to be conducted on a 3+2 axis machine tool. On a 3-axis machine tool the tool axis must remain vertical, although it may move in the X, Y or Z axes freely. A 3+2 axis machine tool follows a similar rule where the tool axis cannot be altered mid-cut. However, the *+2* axes mean that the Z-axis can be manipulated between cuts. This allows much more freedom, with the tool able to point in a specific direction to cut normal to angled surfaces or machine non-vertical slots.

So, for this project, a tool angle could be defined based on a best-fit XY plane. However, the elliptical shape of the vane edge that needed to be cut meant that at times the ball-nose tool would cut at its bottom (*Figure 34*). Cutting tools (especially ball-nose tools) usually perform best when cutting with their side or at a wider point on their tip radius. This is because closer to the tip the effective radius of the tool is smaller, and accordingly that point will have a reduced speed (*Figure 35*). This lowered speed negatively affects cutting ability.

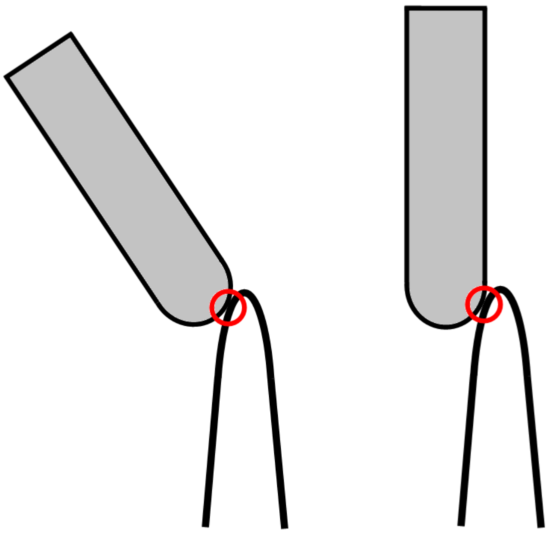

Figure 34 - A diagram showing how the tool angle can affect which part of the tool is used to cut a surface

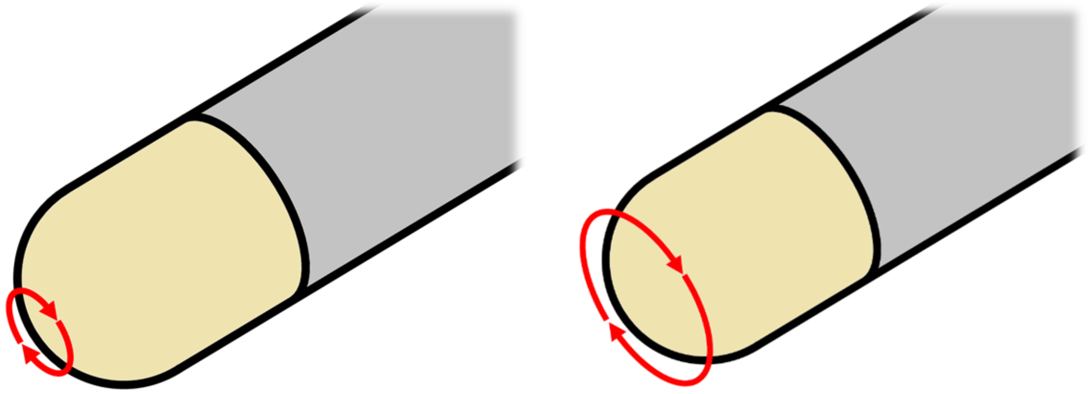

Figure 35 - Diagrams highlighting the difference in effective cutting lengths per revolution

Another issue is that although the particular tool used had 10 flutes (cutting edges), only two of those flutes extended to the bottom of the tool. An example of this can be seen in Figure 36. This led to a lot of rubbing rather than cutting, generating heat and making it even harder to machine the material. The solution for this was that a 5-axis machine tool had to be used. A 5-axis tool allows simultaneous movement of the tool and tool axis, meaning the tool can constantly cut on its edge even as the surface orientation changes.

Figure 36 - An image of a carbide, ball-nose cutting tool where the teeth finish part way round the end radius

Summary

Hopefully this document will have provided an insight into the type of work conducted by the AAC team in Birmingham, as well as the different approaches that can be used to machine certain materials and parts. When machining new and different materials the approach must change or else the risk is run of severely damaging the tool or workpiece after only a small number of cuts. Concepts outlined in the two case studies can be applied to many other scenarios, such as minimising hoop stress by cutting any slots into a cylinder at larger intervals and how CAD and CAM can be combined into an adaptive process.

Subtractive manufacturing is still incredibly widely used and trusted throughout the world. But manufacturing is continually evolving and, with the surge in growth of alternate and hybrid techniques, a good grounding in how to adapt to new situations can serve well.

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