

# Wire-EDM: a potential manufacturing process for gamma titanium aluminides in future aero engines

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Received: 17 May 2017 / Accepted: 28 July 2017 / Published online: 11 August 2017  
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**Abstract** Intermetallic TiAl-based alloys represent an important class of lightweight and high-temperature structural materials, ideal for future aircraft engines, with a potential to replace the extensively used nickel-based superalloy Inconel 718. However, due to their improved strength, the manufacturing of components from conventional machining processes is nearly impossible and results in high tool wear. Recent advancements in wire electric-discharge-machining (wire-EDM) technology have made the process capable of cutting hard materials with accuracy, confirming to tight quality standards, meeting huge production targets, in a flexible and an inexpensive manner. In Germany, recent research on wire-EDM of Inconel 718 has shown negligible white layer and an acceptable fatigue performance, in producing the fir tree slots in jet engines. This paper reviews the feasibility of wire-EDM as the preferred machining process over traditional broaching process, for gamma titanium aluminides in future jet engine components.

**Keywords** Titanium aluminides · TiAl · Machining · Wire-EDM · Broaching

## 1 Introduction

Today's and future aircraft and aero engine designs are driven by continuous improvement following the objectives set by the Advisory Council for Aviation Research in Europe in

terms of lightweight materials on aircraft and engines, more efficient engine designs with increased bypass ratio, enhanced thermal efficiency, aerodynamic performance, and compact lightweight design [1]. This requires increased pressure ratio leading to higher combustion temperatures and higher mechanical loads on components. Development of enhanced materials, therefore, is paramount for advanced aero engines to meet high strength level at elevated temperatures to support higher compression rates and higher gas temperatures for increased engine fuel efficiency and emission controls.

Nickel- and titanium-based alloys are widely used in turbomachinery for their low strength to weight ratios, corrosion resistance, low thermal expansion, and heat-resistant properties. Due to the extreme thermo-mechanical loads in turbomachinery components, nickel-based super alloy Inconel 718, for decades, is widely used in gas turbines and aerospace engines because of its excellent mechanical properties from cryogenic to elevated temperatures (< 650 °C). The titanium-based lightweight intermetallic gamma titanium aluminides, known for their higher strength to weight ratio, oxidation, and corrosion resistance at high temperatures, are viewed as a possible replacement for Inconel [2].

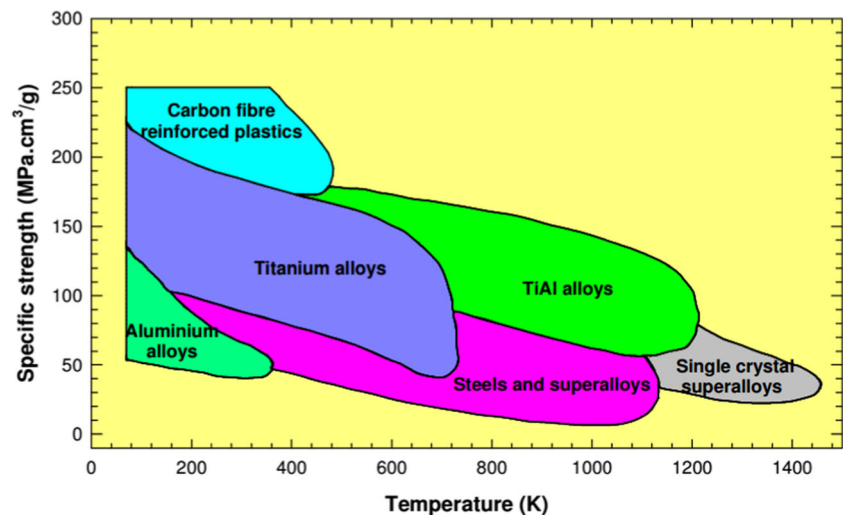
Titanium aluminides represent an important class of alloys with a unique set of mechanical properties and can lead to substantial payoffs in the automotive industry, power plant turbines, and aircraft engines.

Around 30 years of intensive research has achieved the maturity level of TiAl-based alloys that is sufficient to consider this class of materials for critical rotating components in commercial jet engines [3]. The outstanding thermo-physical properties of these alloys mainly result from a strongly ordered structure, involving high melting point, low density, high elastic modulus, low diffusion coefficient, good structural stability, good resistance against oxidation and corrosion, and high ignition temperature when compared to conventional

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**Fig. 1** Temperature dependence of specific strength of various groups of alloys



titanium- and nickel-based alloys. Figure 1 illustrates temperature dependence of specific strength of various groups of commonly known alloys [3]. TiAl-based alloys shows superior specific strength-temperature properties in comparison with classical titanium alloys, steels, and especially nickel-based alloys in the temperature range from 500 to 900 °C [4, 5].

Table 1 compares qualitatively the properties of nickel-based superalloy Inconel 718 for applications in the aircraft industry and evidently the intermetallic TiAl-based alloys exhibit the highest potential for near term applications in future aircraft engines.

While their specific strength is higher than that of competing materials, the room-temperature ductility is poor for most TiAl-based alloys. The other major problem arising from their high strength is poor manufacturability to form a component from traditional cutting techniques, such as milling, turning, and grinding, that result in high tool wear and incurs astronomical costs in terms of time and money.

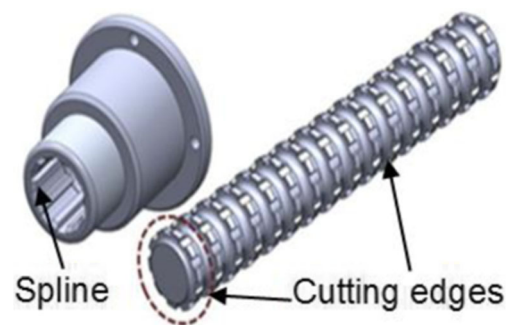
The aim of the present work is to review currently used machining method broaching (for Inconel) and compare it with emerging wire-EDM (for potential TiAl alloys). To incorporate these outstanding materials in jet engines, the aerospace industry must be convinced about the safe manufacturing of parts in compliance with the critical safety regulations primarily concerned with surface integrity and the engine fatigue life. For critical parts used in engines, the adopted manufacturing process should produce parts that are

dimensionally accurate with acceptable surface finish, on a macro level. On the micro level, the process must be evaluated for fatigue life and surface integrity parameters, such as microhardness values, presence of white layers, and the magnitude of residual stresses in the subsurface.

## 2 Broaching

Among machining operations, broaching is an old but important process capable of producing all imaginable profiles unachievable by other machining processes such as rectangular slots, keyways, guideways, splines, gears, and turbine blade hubs for aircraft engines, with repeatable and reliable accuracy. Figure 2 shows a broach, a multiple-point cutting tool with several rows of teeth, each slightly larger than its predecessor and as it moves past the workpiece, all roughing, semi finishing and finishing steps are accomplished in a single stroke of machine. As it eliminates additional finishing operations, the surface integrity of the broached component is directly determined by the process itself [6–12].

Broaching has been used for cutting complicated fir tree slots in jet engines.



**Fig. 2** Spline cut from broach tool with multiple cutting edges

**Table 1** Comparison of Inconel and titanium aluminides

Properties	Inconel 718	TiAl
Density ( $\text{g/cm}^3$ )	8.44	~ 4.0
Yield strength (GPa)	0.46	0.4–0.8
Working temp ( $^{\circ}\text{C}$ )	< 650	< 900

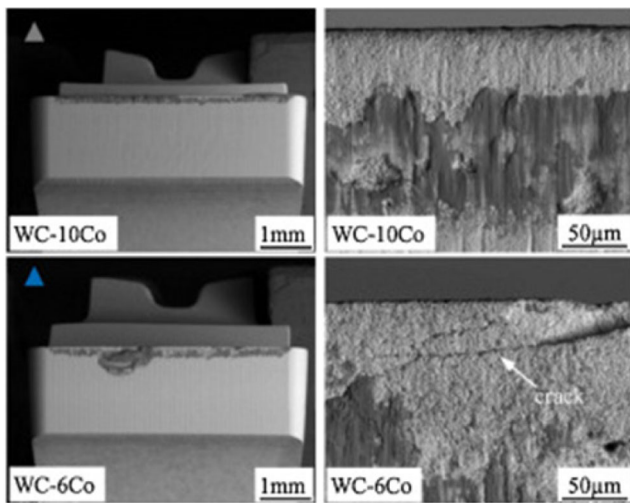


Fig. 3 Tool wear in orthogonal cutting of Inconel

In the past, due to a lack of alternative, manufacturers had to live with the following limitations of this process that rendered it a costly operation:

**Long lead times:** Most broaching tools are specially designed and procured therefore manufacturing lead times are high for custom made broaches.

**High cost for limited production:** Broaching is economical only for mass production, incurs astronomical costs for limited production.

**Tool wear:** For machining superalloys, tool wear [13–19] is a common problem resulting in spending enormous amount of time and money in re sharpening of tools (Fig. 3).

**Inflexible:** A major drawback is that one set of broaching tools can be used only for a specific profile and cannot adapt to design modifications in the cutting profile which is a common practice for continuous improvement in the existing products.

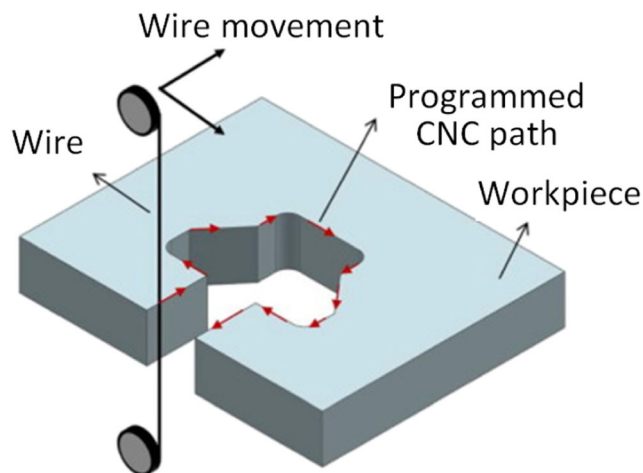


Fig. 4 Mechanism of wire-EDM

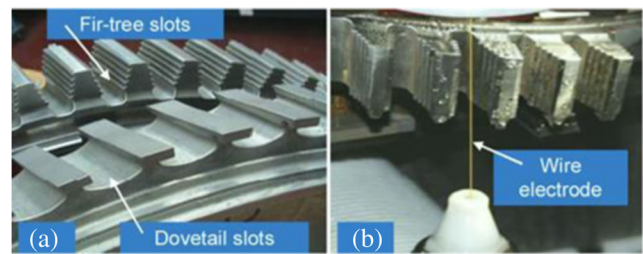


Fig. 5 Fir tree slots by a broaching and b wire-EDM [33]

**High investment:** Broaching machines and tools are a big investment and occupy large floor space depending on the machine stroke that can be 10 ft long.

### 3 Wire electro discharge machining

Developed in the late 1960s, wire-EDM is a process where a continuously traveling wire is used for through sectioning of a workpiece following a computer-controlled contour (Fig. 4); the largest applications has been in the mould and die industry for producing the complex shapes of hard cutting tool materials. The early development work was focused on determining preferred operating parameters [20–22]; however, in the past decade, with the innovations in process monitoring capabilities and equipment improvement, the industrial/academic exploration of wire-EDM is exploding in turbomachinery sector involving nickel-based superalloys and titanium alloys [23–33].

The unique advantages of the process that qualify it to replace traditional machining processes for difficult-to-cut materials are the following:

**No tool wear:** No mechanical contact between wire and the workpiece as cutting is achieved through sparks in a tank of dielectric fluid simultaneously cooling the process and flushing the cut material. In the absence of tool wear, the last part is identical to the first part making the process highly reliable.

**No dependence on material properties:** Material removal is achieved from electric sparks, so, as long as work

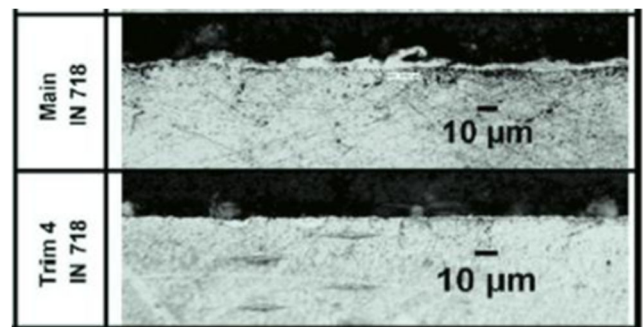
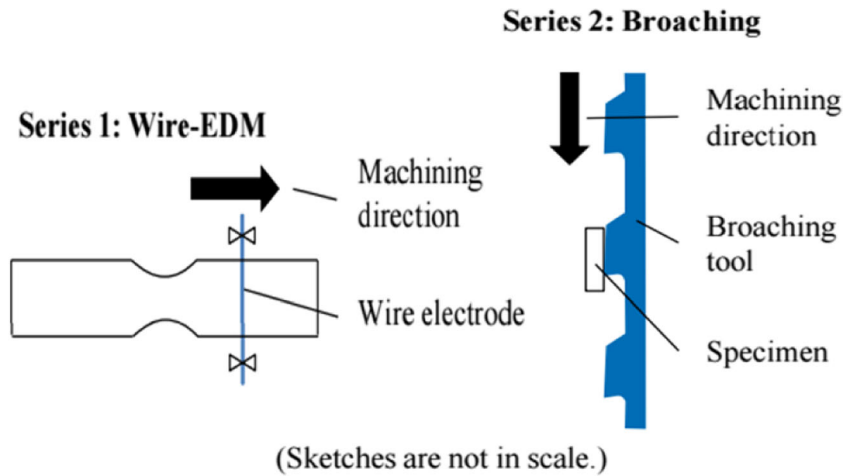


Fig. 6 White layers in main cut eliminated in fourth trim cut, Inconel [26]

**Fig. 7** Preparation of fatigue test samples for wire EDM and broaching [34]



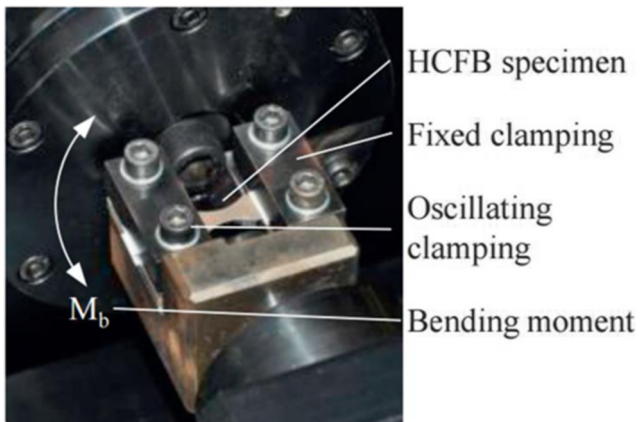
material is electrically conductive, hard or soft, it can be cut with ease, for example, carbide, Inconel, tool steels, stellite, titanium, etc.

*Adaptable to changes:* Amendments in the cutting profiles are quick, convenient, and inexpensive; requires simply loading the modified program file that can be downloaded or emailed.

*Accuracy and finish:* Computer-controlled wire path produces highly accurate parts with extremely fine finish thereby eliminating subsequent finishing processes (Fig. 5).

*Stress free and burr free:* Non-contact nature of metal removal eliminates mechanical distortion to produce burr free and perfectly straight edges even for thin parts.

*Inexpensive:* Wire EDM is economical for small batch size as well as mass production; can be operated 24 h with full automation; and demands low investment in terms of manpower, machine cost, and floor space requirements.

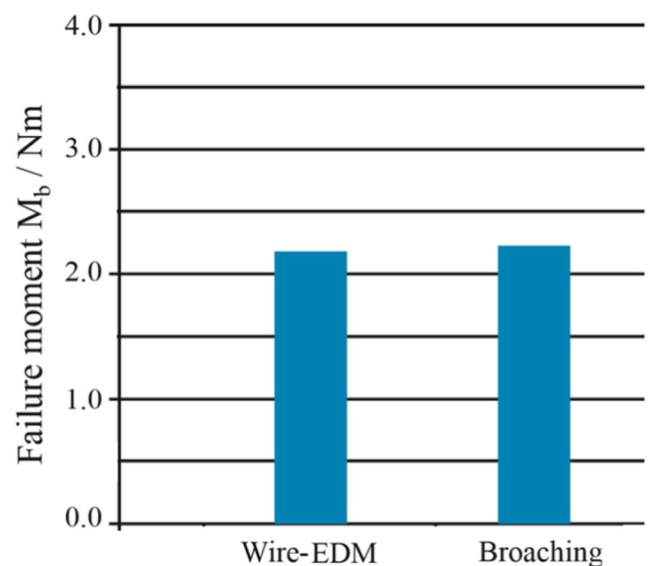


**Fig. 8** High cycle fatigue bending test setup for wire-EDM samples and broached samples [34]

#### 4 Research on Inconel: broaching vs. wire-EDM

##### 4.1 Surface integrity

In 2008, Aspinwall et al. in the UK [26] reported preliminary experimental work with “minimum damage” wire-EDM machine to investigate workpiece surface integrity of Inconel 718; the observed nonuniform white layers from roughing cut decreased steadily with successive trim cuts and near damage free surfaces (essentially zero white layer) were produced after four finishing passes (Fig. 6). The workpiece surface roughness was acceptable and cross sectional micrographs revealed no obvious signs of subsurface microstructural alterations or thermal degradation. In further work by Klocke et al. in 2012, in Germany [29], the reliability and repeatability of a three-pass wire-EDM strategy (rough, finish and polish cuts)



**Fig. 9** Comparable fatigue failure moment for wire-EDM samples and broached samples [34]

developed for Inconel 718 was investigated with ground-breaking success. The cross sectional evaluation of the final cut surfaces ( $< 0.8 \mu\text{m Ra}$ ) showed no evidence of white layer formation, cracking, porosity, phase transition, or microstructural alterations.

## 4.2 Fatigue performance

Later, in 2014, high-cycle fatigue bending (HCFB) tests were carried out by Welling in Germany [34] to compare the performance of the optimized wire-EDM technology against broaching of Inconel 718. The samples, test setup, and test results are shown in Figs. 7, 8, and 9, respectively.

The conclusion of the surface integrity and fatigue analysis of wire-EDM compared to broaching for demanding jet engine components made of Inconel 718 are the following:

While the mechanical behavior of the conventional manufacturing processes brings directional properties into the surfaces with detected grain deformations, the wire-EDMed surfaces are isotropic. The high-cycle fatigue tests showed failure moments in the same magnitude for the broached and wire-EDMed specimen. This result confirms that up-to-date wire-EDM machine tool technologies are capable of generating surface integrities and accompany fatigue resistant surfaces which are comparable with conventionally manufactured surfaces. Especially for the manufacturing of the demanding production of fir tree slots, the research exhibits that wire-EDM is a potential alternative to the broaching process even in terms of the component strength.

While minimum damage cutting of various nickel and titanium alloys has been demonstrated lately, producing acceptable surfaces in gamma titanium aluminides using EDM and a study of machining induced fatigue comparing broaching and wire EDM has not been reported so far.

## 5 Conclusions

The material properties of gamma titanium aluminides were reviewed against traditional Inconel 718 to emphasize these alloys as potential materials for future aircraft engines. Poor machinability is a major concern and traditional machining processes are incapable of producing commercial parts. Recent research results on employing wire EDM as the machining process for producing fir tree slots in Inconel 718 were analyzed and compared with traditional broaching. In terms of part accuracy, surface finish, surface integrity, and fatigue performance, up-to-date wire EDM machine is able to produce quality commercial parts. Research efforts have been confined to Germany and UK only and machining of TiAl using the

latest wire-EDM machine setup have not been reported lately. More research efforts on TiAl are required in the USA to establish wire-EDM as preferred machining process for fir tree slots and other components in jet engines.

**Acknowledgments** The author thanks Dr. Y.B. Guo at The University of Alabama for his motivation in pursuing research in the evolution of materials and manufacturing processes for future aero engine parts.

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