# CHAPTER 1

# Introduction

International travel that is both quick and economically viable defines our modern era. Due to long term demand for aeroplanes (particulary across Asia Pacific, North America and Europe), Commercial Aviation is one of the fastest growing markets for Titanium and Nickel-based alloys as these materials are commonly used for aircraft engine components and airframe structures (Boeing (2012)).

There are three major systems that comprise a modern aeroplane:

1. The aircraft structure (including the fuselage, wings & landing gears);
2. The Avionics / Guidance Systems;
3. The propulsion system that powers the aircraft.

In recent years there has also been a major focus on reducing Carbon emissions. In the aviation industry this has been achieved by maximising component performance leading to the development of lighter engines, landing gears, wings and support structures. By reducing the overall weight of the aircraft, less fuel is consumed thereby achieving the desired result of decreased Carbon emissions.

Airframe and engine materials are distinguished by their structural weight for various materials classes in modern large commercial aircraft. For example, the fuselage of the most fuel-efficient commercial aircrafts (Boeing 787 Dreamliner and Airbus A350 XWB) is comprised of nearly 50% Carbon Fibre reinforced composites. This approach offers weight savings of on average 20% compared to more conventional Aluminum designs. As a result of this optimum material selection, the use of Titanium alloys has been doubled to approximately 15% of the total airframe structure (Ashraf Imam (2011); Lu (2010)).

It is important to note that at over a third of the structural weight, Titanium is the second most abundant material in the jet engine. This is followed by Nickel-based Superalloys, however by volume, Titanium alloys are the most abundant material in the jet engine (Peters *et al.* (2003)).

Both Titanium and Nickel-based alloys are used as they provide a number of benefits including high temperature properties (e.g. creep), corrosion resistance and a high strength-to-weight ratio (only applied to Titanium). This ensures efficient fuel consumption leading to increased economic operation of flights and a longer operational life.

In addition to both mechanical and chemical properties, cost is also a determining factor in the selection of materials for design. The cost considerations extend from raw material selection through to the production of the finished component. Therefore, a material's producibility (measured by its castability, machinability, formability and weldability) represents an important factor when determining cost.

## 1.1 Motivation

Whilst manufacturing advanced alloy components, up to 50% of the material from the forged semi-finished parts have to be removed by different machining operations. The cost of machining the $\beta$-Titanium and wrought Nickel-based alloy components are especially high due to their poor machinability which is a consequence of their physical, mechanical and chemical properties. In addition to this, heat is generated by the cutting action, which cannot be diffused quickly into the chips' material due to poor thermal conductivity of Titanium. Consequently, heat is concentrated in the front of the rake face of the tool leading to tool softening (Ezugwu (2004)).

More precisely, the relatively low Young's modulus in combination with the high strength of $\beta$-Titanium results in spring-back of the workpiece during the cutting action, causing tool rubbing at the flank face, chatter and tolerance problems. Additionally, during the cutting action fresh metallic Titanium surfaces are produced. Due to the high chemical reactivity of Titanium, chemical reactions occur between the tool and the workpiece leading to built-up edge formation (BUE). Consequently, this leads to rapid destruction of the cutting tool and a decrease of the quality of the finished workpiece (Peters & Leyens (2005)).

Wrought Nickel-based alloys also have a tendency to weld with the tool material and form a BUE at the high temperature generated during machining. The presence of hard abrasive Carbides in the Nickel-based alloy microstructure is also detrimental to the machinability. The austenitic matrix workhardens rapidly during machining which generally increases the rate of tool wear. If the finished parts were assembled from prefabricated components, welding or brazing would be required.

This may cause microstructural transformations leading to increased notch-sensitivity or to the formation of undesired $\delta$-phase (Choudhury & El-Baradie (1998)). Consequently, machining from a single workpiece is highly preferred.

The resultant characteristics of both Titanium and Nickel-based alloys cause high temperature and stresses in the cutting zone. This leads to accelerated tool wear and a poor surface quality, dependent upon the material of the tool and the cutting conditions employed. As a consequence, only low cutting speeds can be used compared to the machining of Aluminium and Steel (Schulz & Moriwaki (1992)).

With the automation of manufacturing processes, chip-size control becomes an essential issue in machining operations. This enables a more efficient manufacturing process (Altintas (2012)). Typically, the cutting process has to be interrupted regularly in order to remove the long chips formed from the process zone. When machining, short-breaking chips are desired as long chips may damage the finished workpiece surface, break the cutting inserts or even hurt the operator. The ability to control the size of chips formed will contribute to a more stable machining process, a better-surface finish as well as increased productivity.

In order to optimise the machining process, further study of short-breaking chips is imperative. It has been found that this can be improved by the use of chip breakers, which are designed to break long chips into shorter fragments at regular intervals (Paul *et al.* (2008)). However, as chip breaking limits are determined by material properties, the cutting speed and the cutting tool geometry (Zhou (2001)), chip breakers alone cannot entirely improve machinability for advanced alloys with low heat conductivity and high strength such as Titanium and Nickel-based alloys.

Extensive research studies on free-machining alloys have already demonstrated that short-breaking chips can be obtained by altering their chemical compositions or by forming lubricating or abrasive inclusions, therefore, chip fracture can significantly be improved (Klocke (2011)). For example machining of Steel can be improved with the addition of Lead, Sulphur or Phosphorous.

## 1.2 Research objectives

The aim of the work presented in this Thesis is to demonstrate the successful development, characterisation and manufacture of free-machining alloys with optimised mechanical properties in reference to the two commercially available Nickel and Titanium alloys on which the free-machining alloys are based. This research will show that by making minor changes to the composition of the two reference and difficult to machine Titanium and Nickel-based alloys, a major improvement is noted in relation to their machinability whilst maintaining optimal mechanical properties of the modified free-machining alloys.

Initial studies led and conducted by Rösler and his coworkers (Feyerabend *et al.* (2009); Jencus *et al.* (2007); Rösler *et al.* (2005a); Siemers *et al.* (2006, 2007)) clearly demonstrate that the addition of rare earth elements such as Lanthanum (La) to $\alpha$+$\beta$ Titanium alloys has the desired effect of improving the metal cutting operation as short breaking chips are formed. In addition to this, cutting forces were reduced by more than 20% leading to increased tool life and an improvement in surface quality (Rösler *et al.* (2008)).

To date very little work has been carried out in relation to improving the machinability of metastable $\beta$-Titanium alloys despite these alloys being heavily used in industry. For example, metastable $\beta$-Titanium based alloys are used to develop components within the Aviation Industry as well as Space Travel. The Automated Transfer Vehicle for the International Space Station is equipped with Titanium propellant tanks, of which the half-shells are made of Ti 15V 3Al 3Cr 3Sn (Ti-15-3) (Peters *et al.* (2003); Radtke (2004)). Ti-15-3 is also used in current generation aircrafts like the Boeing 777 for springs and tubes in the brakes (Bania (1993); Nyakana *et al.* (2005)).

In order to investigate how the machinability of metastable $\beta$-Ti alloys can be enhanced, a decision was taken to evaluate the influence of La in the machinability of the metastable Ti-15-3 within the scope of this research work.

Another reason behind pursuing this line of research is that it has been shown that further complications are expected when machining $\beta$-Ti alloys compared to the $\alpha$+$\beta$-Ti alloys which can be machined at relatively higher speeds (Arrazola *et al.* (2009)). This study clearly shows that $\beta$-Ti alloys with increased mechanical properties (e.g. hardness and hot tensile strength) as well as a chemical composition with an elevated Mo equivalent value are difficult to machine.

As wrought alloys require extensive machining in comparison to Ni-based alloys that are cast, Alloy 625 is studied within the framework of this research as it is traditionally used in aerospace industry for jet engine exhaust systems as well as in chemical process industry (Eiselstein & Tillack (1991)). The addition of Silver (Ag) as a free-machining additive for Alloy 625 was patented by Rösler & Siemers (2011) and its benefits should now be studied in depth.

Until now there is no published research on free-machining precipitation-hardened-Nickel-based alloys (such as Alloy 625). Currently, the only reported existing free-machining Nickel-based alloy is Alloy R-405. Its high Sulphur content enhances the machinability of the solid-solution Nickel-Copper alloy (Special Metals (2004)).

This work was carried out within the $7^{th}$ Research Framework Program (FP7, 2007-2013) of the European Union funded project MaMiNa (Macro Micro and Nano aspect of machining) in order to improve the machinability of the previously mentioned alloys. The MaMiNa Network project combines the work of several institutions based on three different approaches:

- Firstly to enhance manufacturing techniques;
- Secondly to improve the endurance of cutting tools;
- Thirdly to develop free-machining alloys.

With reference to this research work, the object of evaluation is the newly developed alloy (the workpiece) as the cutting tool material remained constant.

It has been clearly established that a thorough understanding of the chip formation mechanism is the key factor influencing machinability. Extensive chip analysis of the commercially available alloys was carried out by Rokicki *et al.* (2010, 2011) from the Slovak Academy of Sciences (SAS). Their evaluation justifies the importance of segmented chips (saw-tooth-like geometry) in the development of free-machining alloys.

In order to clarify the chip formation mechanism of the free-machining alloys whilst cutting at high speeds, quick-stop experiments (Hoffmeister & Wessels (2004)) as well as sample manufacturing were carried out at the Institut für Werkzeugmaschinen und Fertigungstechnik (IWF) of the TU Braunschweig.

As resistance to corrosion is an important chemical property of Ti-15-3 and especially to Alloy 625, a corrosion study was carried out to investigate the influence of La and Ag additions on the corrosion behaviour of Ti-15-3 and Alloy 625 respectively.

## 1.3 Outline of the dissertation

Chapter 2 introduces us to the current developments and discoveries (state of the art) in this field of research to date. It aims to allow us to understand the chip formation mechanism, which we have already established to be the key factor influencing the machinability of Ti and Ni based alloys.

This Chapter also includes detailed literature searches carried out on the machinability of Titanium and Nickel-based alloys, as well as any relevant background information relating to the "microstructure-mechanical properties" relationship about the two commercially available alloys. Moreover, a detailed analysis of earlier research studies, which overcame the challenges of machining difficult-to-cut alloys, is also documented.

Following this, Chapter 3 provides an explanation of the equipment and the experimental methods employed (e.g. thermodynamic calculations and alloy production through to mechanical and chemical testings) for the investigation and the characterisation of the free-machining alloys developed.

In Chapter 4 the various modifications made to the Titanium and Nickel-based alloys are discussed in further detail. Firstly it reminds the reader of the conditions needed to improve machinability with the addition of a second phase precipitate. This chapter also demonstrates that the addition of La to Ti and Ag to Ni respectively are the preferred alloying elements to improve the machinability. The additional alloys that were developed and investigated are also listed in this Chapter.

The following Chapters (Chapter 5 and Chapter 6 respectively) discuss in detail the results of the development of both the free-machined Titanium and Nickel-based alloys. In Chapter 5, a step by step account is given of the development of the Lanthanum-containing alloys, where the results clearly demonstrate the formation of inadequate alloys: a detailed examination of these results is also subsequently provided. It is important to note that of the three alloys produced, the first alloy (Ti-15-3 + La) had acceptable mechanical properties however the machinability still remained poor. The second alloy produced (Ti 15V 3Al 3Cr + La) showed improved machinability however, the mechanical properties could be further optimised. Finally, the third alloy produced (Ti 15V 3Al 3Cr XZr + La) was still not satisfactory due to poor ductility despite improved machinability.

Chapter 5 is concluded with a thorough discussion focused on the mechanism that leads to the poor ductility evident in the final alloy produced (Ti 15V 3Al 3Cr XZr + La).

Similarly, in Chapter 6, a step by step account is given of the development of the Silver-containing alloy. It was necessary to develop only one Silver-containing alloy as increased machinability and optimised mechanical properties were immediately achieved.

Chapter 6 goes on to discuss exactly how the addition of Silver to Alloy 625 produces short-breaking chips leading to increased machinability. It is also important to explain that for the successful production of the Silver-containing Nickel-based alloy, different forging conditions are required compared with the forging process of Alloy 625. The reason for this is further discussed here. Finally in Chapter 6, the effect on the corrosion properties by the addition of Silver to Alloy 625 is also examined.

CHAPTER 2

# State of the Art

## 2.1 Machinability of advanced alloys

Titanium and Nickel-based alloys provide serious challenges for cutting tool materials during machining due to their unique combinations of properties such as high temperature strength, hardness and chemical wear resistance. They are referred to as difficult-to-cut due to the high temperatures and stresses generated during machining. The poor thermal conductivity of these alloys results in the concentration of high temperatures at the tool-workpiece and tool-chip interfaces, consequently accelerating tool wear and increasing manufacturing cost (Ezugwu (2004)).

Machinability of a material can be defined and measured as an indication of the ease or difficulty it can be machined (Klocke (2011)). Parameters subjected to state changes during machining can therefore be used as evaluation parameters for judging machinability. Machinability of a material may be therefore assessed by tool life, metal removal rate, cutting forces and surface finish (Trent & Wright (2000)). It is often sufficient to use a single dominant parameter to evaluate machinability.

### 2.1.1 Machining process

Machining is a material removal process. Conventionally, machining is defined as removing metal by mechanically forcing a defined cutting edge through a workpiece. Almost all metals and alloys (hard or soft, cast or wrought, ductile or brittle, with high or low melting point) are machined.

Machining includes processes such as turning, milling, boring, drilling, facing and broaching, which are all chip-forming operations. It must be understood that chips are produced by shearing action and not by cutting. During machining, lot of heat is generated and the temperature of the cutting edge of the tool may reach 650-700°C (Kaushish (2010)). The tool must maintain its hardness even at such elevated temperatures. This property of retaining its hardness at elevated temperatures is called “red hardness”. Cutting tools develop the property of red-hardness due to addition of Tungsten and Molybdenum to high Carbon steel. These days, manufacturers use Tungsten Carbide (also known as Cemented Carbide) as the main material in some high-speed drill bits.

The hardness of Nickel and metastable $\beta$-Titanium alloys increases significantly upon heat treatment, hence, they are referred to as age hardenable. Formation of second phase precipitates makes the alloy both stronger and more abrasive and thus more difficult to machine. Advantage, therefore, lies in machining in the softer state. Typically, the component is machined to near finish dimensions in the solution treated condition, then age hardened and finally machined to generate the desired surface finish and to eliminate any distortion associated with heat treatment.

In the last few decades, some entirely new machining processes have been developed, such as the ultrasonic machining, thermal metal removal processes, electrochemical material removal processes, laser machining processes etc., which are very different from the conventional machining processes. However, the conventional metal cutting operations are still the most widely used fabrication processes, a \$60 billion per year business (Zhou (2001)). It is therefore still essential to develop a more fundamental understanding of metal cutting processes.

### Semi-orthogonal cutting

The basic operation of turning, also called semi-orthogonal cutting in the research laboratory (Fig. 2.1), is one of the most commonly employed term in experimental work on metal cutting. The work material is held in the chuck of a lathe and rotated. The tool is held rigidly in a tool post and moved at a constant rate along the axis of the bar, cutting away a layer of metal to form a cylinder or a surface of more complex profile. In the process of turning, a cylindrical shape is generated as a result of the combined movement of the work piece and the tool (Kaushish (2010)).

The cutting speed ($v_c$) is the rate at which the uncut surface of the work passes the cutting edge of the tool, expressed in m/min. The feed ($f$) is the distance moved by the tool in an axial direction at each revolution of the work. The depth of cut ($a_p$) is the thickness of metal removed from the bar, measured in a radial direction. The product of these three gives the rate of metal removal (Eq. 2.1), a parameter often used in measuring the efficiency of a cutting operation (Gupta (2009)).

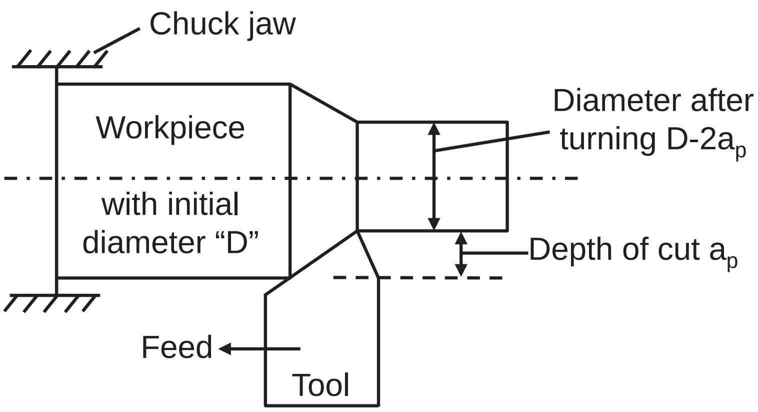

**Figure 2.1:** Schematic of conventional metal cutting operation: Turning on the lathe.

$$v_c \cdot f \cdot a_p \;=\; rate\ of\ metal\ removal \tag{2.1}$$

Cutting speed is usually chosen between 3 and 200 m/min. However, in modern high speed machining, speed may be as high as 3500 m/min when machining Aluminium alloys. Computer-controlled machine tools have the capacity to maintain a constant cutting speed, $v_c$, by varying the rotational speed (RPM) as the workpiece diameter changes.

### 2.1.2 Chip formation mechanism

The side of the chip in contact with the cutting tool is normally flat and smooth whereas the other side, which is the free workpiece surface, is rough. Depending on the materials properties and cutting parameters, in machining four basic types of chips are known to form: continuous, segmented, wavy or even separated chips if extreme cutting conditions are used (Grzesik (2008)).

Figure 2.2 illustrates examples of chips obtained in case of Aluminium, Brass, Chromium Steel and Titanium alloys. The first three alloys form continuous chips whilst Titanium forms a segmented chip with the same cutting parameters. Chip formation pictures were taken during experimental work at the Technical University of Lodz, Poland, in the framework of MaMiNa school “Machine Tools and Machining” in March 2009.

The surface of the tool over which the chip flows is known as the *rake face*. The *cutting edge* is formed by the intersection of the rake face with the *clearance face* or *flank* of the tool. The tool is designed in a way and held in such a position that the clearance face does not rub against the freshly cut metal surface as illustrated in Figure 2.2.

A positive rake angle is recommended for semi-finishing and finishing operations whenever possible. Positive rake geometry minimises work hardening of the machined surface by shearing the chip away from the workpiece in an efficient way in addition to minimising built-up-edge. Sharp insert edges are useful in preventing material build-up and improving surface finish during machining. Using a large nose radius wherever part geometry does not demand otherwise can reinforce the cutting edge (Ezugwu (2004)).

As illustrated in Figure 2.3, Ti 15V 3Al 3Cr 3Sn (Ti-15-3) forms continuous chip characterised by fine lamellar structure at low cutting speeds (e.g. 20 m/min) whereas segmented chips form at higher cutting speeds (from 40 m/min).

Chip types can also be classified according to their degree of segmentation $G$ (Rösler *et al.* (2005b)) as presented in Equation 2.2 :

$$G = \frac{h_{max} - h_{min}}{h_{max}} \tag{2.2}$$