Chapter 1

Introduction

1.1 BACKGROUND AND MOTIVATION

High strength alloys such as nickel, titanium, advanced engineering materials like ceramics and composites are being widely used in aerospace, automotive, medical and nuclear industries due to its inherent physical and mechanical properties. Most of the components produced from advanced materials such as titanium and nickel based alloys are made to be used in aerospace industries. However conversion of these high strength materials in to engineering products with conventional machining is very difficult and uneconomical. This is due to the excessive generation of heat at the cutting zone and difficulties in heat dissipation due to low thermal conductivity of these materials. High material hardness, high strength together with high temperature at the cutting zone results in excessive tool wear and thus shorter tool life and poor surface quality. Thus the application of new hybrid machining methods has been introduced in recent years in the field of machining difficult-to-machine materials. Hybrid machining process uses the combination of two or more of the machining methods to overcome the disadvantages associated with non-aided machining process. The hybrid machining processes such as electrical discharge grinding; vibration assisted machining; magnetic assisted machining; cryogenic machining and thermally assisted machining are attracted by researchers to machine difficult-to-machine materials.

1.2 THERMALLY ASSISTED MACHINING

Thermally assisted machining (TAM) is a hybrid process that utilizes an external heat sources to rise the temperature at the shear zone of cutting area to enable the processing of the material. Preheating lowers the yield strength and allows ductile deformation behavior in materials. This process employs various preheating methods and mechanisms such as laser, plasma, gas torch, induction and furnace preheating. In the gas torch preheating, the heating of the material is carried out by burning a mixture of liquid petroleum gas and oxygen. Induction preheating is the process of
heating an electrically conducting object by electromagnetic induction. An induction preheating system consists of an electromagnet, through which a high frequency alternating current is passed.

In recent decades, the plasma assisted machining (PAM) and laser assisted hybrid machining (LAHM) have been studied for improving the machinability of difficult to machine materials. Heating during PAM is provided by direct current. Transferred arcs generate thermal or equilibrium plasma. Thermal arc plasma generators consist of a tungsten cathode and a cooled nozzle through which the plasma gas flows. The nozzle serves as an anode when used with non-conducting workpiece. With conducting materials, the arc is transferred to the workpiece which works as an anode. Very few studies on plasma assisted machining (Leshock et al., 2001; Wang et al., 2003) have been performed on difficult to machine material.

The schematic illustration of laser assisted hybrid machining (LAHM) is shown in Figure 1.1. In LAHM, a laser is used as the heat source with its beam focused on the workpiece for a small projected area. A part of laser energy is absorbed by workpiece material in front of the cutting tool. The induced temperature is sufficiently high to cause reduction in material yield strength/hardness in the surface layer of the material. The heated volume of material in radial direction can be removed with conventional tool material thereby improving the machinability benefits. The researcher has adopted this hybrid machining method to machine various difficult-to-machine materials such as ceramics, metals and composites.

![Figure 1.1 Schematic illustration of laser assisted hybrid machining](image-url)
1.3 OVERVIEW OF DIFFICULT TO MACHINE MATERIALS

Difficult to machine materials are defined as the materials which during machining operations produce excessive tool wear, heat and/or cutting forces, difficulties in chip formation and/or poor surface quality. The difficult to machine materials are broadly classified into three categories namely: hard materials, ductile materials and non-homogeneous materials. This classification and its sub-categories are demonstrated in Figure 1.2. The main properties to consider hard materials as difficult to machine are high hardness and strength together with poor thermal conductivity which can result in short tool life, low productivity and poor surface quality (Ezugwu, 2005). On the other hand another category of materials such as polymers and low carbon steels are considered to be difficult to machine due to high ductility and strain rate. The main problems in machining these materials are the chip formation, geometrical accuracy and surface quality of the machined components (Hong and Ding, 2001; Kakinuma et al., 2008). Composites are also known as difficult-to-machine materials due to shorter tool life and/or poor surface quality. This is mainly attributed to the fact that composites are made of a combination of different materials with different properties which are neither homogenous nor chemically combined.

Figure 1.2 Classification of the difficult to machine materials
1.4 SUPER ALLOYS – AN OVERVIEW

Super alloys, also known as heat resistant super alloys or high performance alloys, are alloys which exhibit excellent mechanical strength, ductility and creep strength at high operating temperatures, high fatigue strength and typically superior corrosion and oxidation resistance at elevated temperature. These properties makes them ideal choice of materials for an industrial applications in aircraft, submarines, nuclear reactors, dies for hot working of metals and petrochemical equipment, biomedical and cryogenic applications.

Super alloys generally contain nickel (Ni), chromium (Cr), cobalt (Co), molybdenum (Mo) and iron (Fe) as major constituent elements. Others are aluminium (Al), tungsten (W), titanium (Ti) and so on. The role of these alloying elements is to enhance the characteristics of super alloys. Ni stabilizes alloy structure and properties at high temperatures. Co, Mo and W increase the strength at elevated temperature. Cr, Al, Si enhances resistance to oxidation and high temperature corrosion. Carbon (C) increases creep strength. Super alloys typically have a matrix with an austenitic face centered crystalline structure.

Super alloys are classified into three groups which are iron-nickel, nickel and cobalt based alloys. These are the most widely used group of super alloys in the industry. Iron-nickel based alloys generally contain 29-67% Fe, up to 22% Cr and 9-44% Ni. This alloy includes the families of alloys such as Incoloy, Ascoloy and so on. Nickel based super alloys contain nickel as the base metal. The major alloying elements are chromium and cobalt; lesser elements include aluminium, titanium, molybdenum, niobium and iron. Inconel, Nimonic, Hastelloy and Rene 41 are included in this group. Cobalt based super alloys consist of cobalt (around 40%) and chromium (≈20%) as their main components. Other alloying elements include nickel, molybdenum and tungsten. Compared with the iron based super alloys, the advantages of nickel alloys are its high working temperature, strong antioxidant corrosion capacity. Compared with the cobalt alloys, nickel alloys can work at a high temperature and stress condition.
1.5 NICKEL BASED SUPER ALLOYS

Nickel (Ni) based alloys constitute a largest group of super alloys. These Ni based super alloys are mainly used in applications requiring high corrosion resistance and high strength at elevated temperatures. These alloys currently constitute over 50% of the weight of advanced aircraft engines. Alloys of this grade contain 38-76% Ni and remaining elements are Cr, Co and Mo. Common types of Ni based alloys includes Hastelloy, Inconel, Nimonic, Rene, Udimet and Waspaloy. The Ni based super alloys are broadly classified under the groups as Group A, Group B, Group C and Group D as shown in Figure 1.3.

![Classification of Nickel-based alloys](image)

**Figure 1.3 Classification of nickel based super alloys**

Group A contains 95% or more nickel and has moderate mechanical strength and high toughness. This Group A alloys are being applied in the field of electronic parts, resistance to corrosion applications such as handling alkaline solutions and foods. Group B consists of the nickel copper alloys. The alloys in this group have higher strength and slightly lower toughness than those in Group A. These Group B alloys are being applied for marine fixtures, pumps, valves and piping systems for seawater application. Group C consists largely of the solid solution nickel-chromium and
nickel-chromium-iron alloys, which are similar to the austenitic stainless steels. These Group C alloys are widely used in the aircraft engine for making combustors, ducting, exhaust systems, thrust reversers etc. Group D, which consists primarily of the age-hardenable alloys, has two sub groups: Alloys in the unaged and aged condition. The alloys in Group D have high strength and hardness, particularly when aged. The Ni based alloys are widely used in hotter sections of gas turbines and combustor parts. Figure 1.4 shows the aircraft engine in which the components of the Ni-based alloys are identified.

![Figure 1.4 Applications of nickel based super alloys](image)

1.6 MACHINING CHALLENGES FOR INCONEL 718 ALLOY

Inconel 718 is precipitation hardenable Ni based alloy, containing significant amounts of iron, niobium and molybdenum, along with lesser amounts of aluminium and titanium. This material has high yield strength and creep-fatigue properties at a temperature up to 650°C. Inconel 718 alloy has been used for jet engine and high-speed airframe parts such as wheels, discs, casings, blades, impellers, rings shafts, and high temperature bolts and fasteners. The products of Inconel 718 alloy in aerospace and medical application is shown in Figure 1.5.
In the present work, Inconel 718, a nickel based super alloy is taken for investigation. It preserves high shear strength, hot strength, hot hardness and very high temperature resistance. Due to low thermal conductivity of nickel alloy, a high temperature is generated in the shear zone at higher cutting speeds. This effects the built-up edge formation over cutting zone. The drastic increase in cutting temperature leads to shorter tool life and poor surface quality. In addition, the modified microstructure of subsurface, induced tensile residual stress, micro cracks and microhardness variations with white layer formation are the other problems. Furthermore, the hardness of the Inconel 718 alloy increases with increase of temperature up to 650°C. This is due to the presence of hard abrasive carbide particles in the material which is responsible for work hardening. Another machining induced problem in the material is work hardened subsurface resulting higher cutting force. Hence machining of Inconel 718 alloy using conventional machining method is always associated with low cutting speed and thus machining costs is high. These characteristics are responsible for deprived machinability during conventional machining of Inconel 718.

In machining of high temperature super alloys, the cutting fluid plays an important role. But the adverse impact of cutting fluids on the environment and operator cannot be neglected. All these factors sum up a significant cost which is four times the cost of cutting tools used and 17% of the total manufacturing cost. Therefore the feasibility of dry machining or near dry machining has received a significant attention in the past decade as it is reduces the overall manufacturing cost.
as well as eliminates all the negative effects associated with it (Ezugwu, 2005). While coated cemented carbide tools; cubic boron nitride and ceramics has accomplished a substantial achievement in the dry turning of Inconel 718 alloy, shorter tool life; higher cutting force; and surface integrity problems affects the economy. To overcome these issues of conventional machining of Inconel 718 alloy, a laser assisted hybrid machining (LAHM) approach could be an innovative method for improving the machinability.

1.7 SCOPE OF THE PRESENT RESEARCH WORK

The scope of present research work is studied in three phases. In first phase, preliminary heating trials to study the influence of parameters such as cutting speed, feed rate, laser power and laser approach angle, on surface temperature and heat affected depth is carried out without material removal. The experiments are planned based on central composite design in response surface methodology (RSM).

In second phase, the machining experiments are carried out based on full factorial array of experimental design to investigate the influence of machining and laser parameters on machining performance during LAHM. PVD coated tungsten carbide inserts has been used as cutting tool material. The experiments are conducted at an optimized laser approach angle obtained from preliminary heating trials.

Response surface methodology (RSM) and artificial neural network (ANN) based modeling approach is used to develop empirical relationship between input parameters and performance measures. Then the optimal levels of laser assisted hybrid machining parameters are determined using desirability function approach. The benefits of LAHM compared with conventional machining are analyzed. The chip morphology has been carried out to study the benefits of LAHM.

In third phase, the tool life, tool failure modes and surface integrity studies at the optimal cutting condition has been carried out on the workpiece and the results are analyzed. Additionally, the tool wear progression is compared with conventional machining.
1.8 THESIS OUTLINE

Chapter 1 gives a brief introduction about the hybrid machining methods, thermally assisted machining, an overview of difficult-to-machine materials, super alloys, nickel based alloys, machining challenges for Inconel 718 and research scope.

In Chapter 2, review of literature for conventional machining and laser assisted hybrid machining of Inconel 718 alloy are discussed. The research gap, objectives of the present study, methodology and summary of review of literature are reported.

In Chapter 3, a description about experimental setup, measuring instruments, experimental procedure, material chosen for the present investigation, selection of cutting tool, selection of process parameters and its levels are discussed.

In Chapter 4, the description for preliminary laser heating trials, experimental procedure, results and discussion for preheating experiments are discussed. Further, the optimization and empirical modeling of parameters using response surface methodology is discussed.

In Chapter 5, the description for laser assisted hybrid machining (LAHM), experimental procedure, results and discussion are discussed. The effects of parameters on responses are analyzed using response surface plots and main effect plots.

In Chapter 6, statistical model development using response surface methodology (RSM) and artificial neural network (ANN) for each response criteria in terms of input parameters such as cutting speed; feed rate; and laser power is described. The developed models are validated for goodness of fit.

In chapter 7, the benefits of laser assisted hybrid machining of Inconel 718 alloy compared to conventional machining are discussed. The machining performance indices such as cutting forces; surface roughness; and flank wear are considered to effectively explore the benefits of LAHM over conventional machining. Further, the chip morphology study is carried out.
In chapter 8, the optimization of laser assisted hybrid machining parameters for single and multi-response criteria using desirability function approach is carried out. Then, tool life study, tool failure modes, surface integrity and micro hardness at the optimum levels of process parameters are discussed. The results are analyzed and discussed in detail.

In Chapter 9, the major conclusions and contributions of the thesis, limitations and future research directions are discussed.