ROSEMAR BATISTA DA SILVA

PERFORMANCE OF DIFFERENT CUTTING TOOL MATERIALS IN FINISH TURNING OF Ti-6Al-4V ALLOY WITH HIGH PRESSURE COOLANT SUPPLY TECHNOLOGY

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Tese apresentada ao Programa de Pós-Graduação em Engenharia Mecânica da Universidade Federal de Uberlândia - modalidade Sanduíche no Exterior realizado com a London South Bank University – Londres, Reino Unido, como parte dos requisitos para a obtenção do título de DOUTOR EM ENGENHARIA MECÂNICA.

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To my parents, Mrs. Rosalina Batista and Mr. Antônio Caetano,
and sisters
Ms. Rejaine Inês, Ms. Jeane Inês, Ms. Josiane Inês
for their encouragements and love.
To the memory of Mr. Jovino Batista da Fonseca,
my unforgettable grandfather.

DECLARATION

The research presented in this thesis is the original work of the author except where otherwise specified by references, or where acknowledgements are made. The project was carried out at the Machining Research Centre, Faculty of Engineering Science and the Built Environment (England), and Laboratory of Teaching and Research in Machining, Faculty of Mechanical Engineering of Federal University of Uberlândia (Brazil) under the supervision of Professor E. O. Ezugwu and Professor A.R. Machado, respectively. This work is being submitted for the degree of Doctor of Philosophy – Ph.D. jointly to London South Bank University (UK) and Universidade Federal de Uberlândia – Brazil.

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ABSTRACT

This study investigated the machinability of Ti-6Al-4V alloy with newly developed cutting tools such as uncoated (T1 and T3) and coated (T2 and T4) cemented carbides, Polycrystalline Diamond (PCD) – T5 and T6 inserts, Cubic Boron Nitride (CBN) – T7,T8,T9 inserts, SiC Whiskers Reinforced Ceramic (T10) insert, and Al_2O_3 base (T11) and Si_3N_4 base nano-grain size ceramic (T12) inserts using various cooling environments such as high pressure coolant supplies at pressures of 7 MPa, 11 MPa and 20.3 MPa, argon enriched environment and conventional coolant flow at high speed machining conditions typical of finish turning operation. Tool life and failure modes, wear mechanisms, component forces generated, surface integrity, surface finish and chip form data were used to assess the performance of the different cutting tools and cooling environments investigated. PCD and carbide inserts gave the best performance, in terms of tool life, when machining Ti-6Al-4V alloy. In general coarser (T1 and T4) grain size carbides and PCD (T5) inserts gave the best overall performance in terms of lower wear rate hence longer tool life compared to finer grain (T2,T3 and T6) grades. Encouraging tool life can be achieved when machining with high pressure coolant supply relative to conventional coolant flow and in the presence of argon. Tool lives generally increased with increasing coolant pressure due to the ability of the high coolant pressure to reduce the tool-chip contact length/area and to lift the chip, thereby providing adequate lubrication at the tool-chip interface with consequent reduction in friction. Machining with T1, T4 and T10 inserts in presence of argon was only able to prevent chip ignition with no improvement in tool life, due probably to the suppression of the cooling and/or lubrication characteristics of argon gas when machining at cutting conditions investigated. Up to 8 fold improvement in tool life were achieved when machining with PCD inserts relative to carbide inserts under conventional coolant flow. All the grades of CBN inserts gave poor performance during machining due to accelerated nose wear and, in some cases, severe chipping of the cutting edge associated with a relatively high diffusion wear rate that tends to weaken the bond strength of the tool substrate. An increase in the CBN content tends to accelerate notch wear rate, consequently diminishing tool life under the cutting conditions investigated. Micron and nano-grain size ceramics did not demonstrate satisfactory performance in terms of tool wear rate and tool life, due to severe abrasive wear and chipping of the cutting edge, hence the poor machined surfaces generated. Nose wear was the dominating tool failure mode when machining with carbide, PCD and CBN (T7) inserts due to a reduction in tool-chip and tool-workpiece contact lengths and the consequent increase in both normal and shear stresses and temperature at the tool tip, while severe notching and chipping occurred when machining with CBN (T8 and T9) and micron grain size ceramics. Severe notching also occurred when machining with nano-grain ceramic inserts, often leading to catastrophic tool failure at speeds in excess of 110 m min^{-1}. Machining with PCD tools gave lower cutting forces than carbides inserts. Surface roughness values generated with carbides, PCD and CBN inserts were generally within the 1.6 μm rejection criterion for finish machining and above 2 μm when machining with all grades of ceramics employed. Micrographs of the machined surfaces show that micro-pits are the main damage to the machined surfaces. Microhardness of the machined surfaces when machining with carbides varied randomly around the hardness values of the workpiece material prior to machining. Machining with PCD tools generally led to softening of machined surfaces. Increase in cutting speed generally led to increased hardness when machining with the larger grain size PCD (T5) tool using conventional coolant flow and with coolant pressures up to 11 MPa. No evidence of plastic deformation was observed on the machined surfaces and the surface integrity of the finish machined surfaces is generally in agreement with Rolls–Royce CME 5043 specification.

Keywords: Titanium alloy, High Coolant Pressure, Various cutting tools, Tool life, Surface integrity

DA SILVA, R.B. Desempenho de diferentes Materiais de Ferramentas de Corte no Torneamento de Acabamento da liga de titânio Ti-6Al-4V com a Tecnologia de Aplicação de Fluido de Corte à Alta Pressão, 2006, 299 f. Tese de Doutorado, Universidade Federal de Uberlândia, Uberlândia.

RESUMO

Este estudo visa avaliar a usinabilidade da liga de titânio Ti-6Al-4V utilizando várias classes de diferentes materiais de ferramentas de corte tais como metal duro sem revestimento (insertos T1 e T3) e com revestimento (insertos T2 e T4), PCD – insertos: T5 e T6, CBN – insertos: T7,T8 e T9, cerâmicas Whiskers (inserto T10), e nano-cerâmicas à base de alumina (inserto T11) e à base de nitreto de silício (inserto T12) em diferentes atmosferas de usinagem (fluido de corte aplicado a altas pressões (HPC) de 7 MPa; 11 MPa and 20,3 MPa, argônio e aplicação de fluido de corte convencional) e em elevadas condições de corte típicas de acabamento (velocidade de corte de 100 m min^{-1} a 500 m min^{-1}, com avanço de 0,15 mm volta^{-1} e profundidade de corte de 0,5 mm constantes). Foram monitorados a vida das ferramentas bem como os mecanismos e tipos de desgaste, as forças de usinagem, a integridade superficial, a rugosidade das superfícies usinadas, a circularidade e os tipos e classes de cavacos produzidos. Os resultados foram utilizados para avaliar a eficiência das diferentes ferramentas de corte e atmosferas de usinagem empregadas na usinagem da liga Ti-6Al-4V. Os resultados mostraram que as ferramentas de PCD e metal duro tiveram o melhor desempenho, em termos de vida de ferramenta, que as demais ferramentas testadas. Em geral, as ferramentas com tamanho de grãos maior, metal duro (T1 e T4) e PCD (T5), apresentaram o melhor desempenho, em termos baixa taxa de desgaste e, consequentemente, vida mais longa, comparada com as ferramentas com tamanho de grãos menores (classes T2,T3 e T6). A utilização da técnica HPC mostrou ser eficiente na usinagem da liga Ti-6Al-4V, em termos de aumento de vida da ferramenta e, consequentemente, de aumento de produtividade, em relação à técnica de aplicação de fluido de corte convencional e com utilização de argônio nas condições investigadas. Em geral, a vida das ferramentas aumentaram com o aumento da pressão de aplicação de fluido de corte devido à sua capacidade de reduzir a área de contato cavaco-ferramenta e de quebrar o cavaco mais eficientemente e, portanto, propiciando uma melhor condição de lubrificação na interface cavaco-ferramenta com conseqüente redução de atrito. A utilização do argônio na usinagem com as ferramentas T1, T4 e T10 nas condições investigadas apenas evitou com que o centelhamento e ignição do titânio ocorresse, além de não propiciar aumento de vida da ferramenta, provavelmente devido à supressão das características de refrigeração e lubrificação que o argônio tem. As ferramentas de PCD apresentaram uma vida cerca de 8 vezes maior que as ferramentas de metal duro quando empregadas com aplicação de fluido de corte convencional. Todas as classes de ferramentas de CBN, em geral, apresentaram baixo desempenho em termos de vida de ferramenta devido ao acelerado desgaste na ponta da ferramenta e, em certos casos, lascamentos da aresta de corte que estão associados com a relativa alta taxa de difusão que ocorre durante a usinagem com titânio, que tende a diminuir a forças de ligações entre os átomos do substrato. Todas as ferramentas de cerâmicas testadas não demonstraram desempenho satisfatório em termos de desgaste e de vida ferramenta durante a usinagem da liga Ti-6Al-4V por causa da ocorrência de desgaste abrasivo e de lascamento da aresta de corte, como também da produção de superfícies usinadas com pobre acabamento superficial. O desgaste de ponta foi o tipo de desgaste predominante durante a usinagem com as ferramentas de metal duro, PCD e CBN (T7) devido à redução da área de contato cavaco-ferramenta e, consequentemente, ao aumento das tensões atuantes e aumento da temperatura na ponta da ferramenta. Já o desgaste de entalhe e lascamento ocorreram durante a usinagem com as ferramentas de CBN (T8 and T9) e com cerâmicas convencionais. O desgaste de entalhe também ocorreu de forma mais acentuada nas ferramentas de nano-cerâmicas, o que levou à falha catastrófica de tais ferramentas quando empregadas em velocidades de corte superiores a 110 m min^{-1}. A usinagem com ferramentas de PCD geraram baixas forças de corte em relação às ferramentas de metal duro. Os valores de rugosidade superficial produzidos com as ferramentas de metal duro, PCD e CBN em geral ficaram abaixo do valor estipulado para critério de rejeição para torneamento de acabamento de 1.6 µm, enquanto que todas as ferramentas de cerâmicas produziram valores de rugosidade acima de 2 µm. A análise metalográfica das superfícies usinadas permitiu identificar pequenas marcas que não comprometeram as superfícies produzidas. A usinagem com ferramentas de metal duro produziu valores de dureza que variam aleatoriamente dentro dos limites inferior e superior de dureza da peça medidos antes da usinagem. Nenhuma evidência de deformação plástica nas superficies de titânio usinadas com todas as ferramentas e condições testadas. Em geral, a integridade superficial das superficies usinadas atendem à norma Rolls–Royce CME 5043.

Palavras-chave: Liga de titânio, Fluido de corte à alta pressão, Várias ferramentas de corte, Vida de ferramenta, Integridade superficial.

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LIST OF SYMBOLS

ϕ	Shear plane angle
ρ	Angle for chip friction
μ	Coefficient of friction
δ	Shear strain at the primary shear plane
σ_f	Normal stress component
τ_f	Shear stress component
σ_{fma}	Maximum normal stress
γ_n	Tool normal rake angle
α_n	Tool normal clearance angle
β_n	Tool normal wedge angle
ε_r	Tool included angle
λ_s	Tool cutting edge inclination angle
τ_{st}	Shear strength of chip material
Al_2O_3	Alumina oxide
ANOVA	Analysis of Variance: a statistical assessment of sample data to decide if differences exist between various groups of data.
C.I.	Confidence Interval of 99% for distribution.
C_2H_5OH	Ethanol vapour
CBN	Cubic Nitride Boron
CCF	Conventional Cooling Flow delivery system
CCl_4	Tetrachloromethane
DOC	Depth of Cut (mm)
DOC	Depth of Cut (mm)
EP	Extreme Pressure
f	Feed rate (mm rev^{-1})
HfC	Hafnium carbide
HfN	Hafnium nitride
HIPed	Hot Isostatic Pressing
HPC	High Pressure Coolant delivery system
HV	Hardness Vickers
ISO	International Standardisation Organisation
k	Constant for the work material
k'_r	Tool minor cutting edge angle
k_r	Tool cutting edge angle
m	meter
Max.	Maximum value of a measured hardness
MgO	Magnesium oxide
Min.	Minimum value of a measured hardness
MM	Multi-Modal Grade of Polycrystalline Diamond insert
MMC	Metal Removal Rate (cm^3 min^{-1})
MQL	Minimum Quantity Lubrication
n	Spindle Speed (rev min^{-1})
PCD	Polycrystalline Diamond
Pn	Cutting edge normal plane
Pr	Tool reference plane

Pre	Working reference plane
Ps	Tool cutting edge plane
Pse	Working cutting edge plane
r	Chip thickness ratio
Ra	Average Surface Roughness
SIALON	Silicon aluminium oxynitride
Si_3N_4	Silicon nitride
STD	Standard Grade of Polycrystalline Diamond insert
T1	Uncoated carbide insert – 883 designation
t_1	Underformed chip thickness
t_1	Actual chip thickness
T1	Uncoated carbide insert – 883 designation
T2	Uncoated carbide insert – 890 designation
T3	Coated carbide insert – CP 200 designation
T4	Coated carbide insert – CP 250 designation
T5	PCD insert – STD designation
T6	PCD insert – MM designation
T7	CBN insert – 10 designation
T8	Solid CBN insert –300 designation
T9	Solid Coated CBN insert – 300-P designation
T10	Silicon carbide whisker reinforced alumina ceramic insert – micron-grain size - WG 300 designation – rhomboid-shaped geometry
T11	Silicon carbide whisker reinforced alumina ceramic insert – micron-grain size - designation WG 300 – squared-shaped geometry
T12	Alumina base nano-grain size ceramic insert – SAZT2 designation
T13	Silicon nitride base nano-grain size ceramic insert – SNCTN1 designation
TaC	Tantalum carbide
TD	Theoretical Density
TiB_2	Titanium diboride
TiC	Titanium carbide
TiN	Titanium nitride
TiAlN	Titanium aluminium nitride
TiZrN	Titanium zirconium nitride
TiO_2	Titanium oxide
T_M	Cutting temperature
V	Cutting Speed (m min^{-1})
Vc	Chip Velocity (m min^{-1})
WC	Tungsten carbide
Y_2O_3	Yttria
ZrO_2	Zirconium oxide

CHAPTER I

INTRODUCTION

The machinability of titanium alloys is generally considered to be poor due to their inherent properties such as chemical reactivity, consequently their tendency to weld onto the cutting tool during machining leading to excessive chipping and/or premature tool failure. The low thermal conductivity of titanium alloys increases temperature generated at the tool-workpiece interface, adversely affecting tool life. They also exhibit tendency to form localised shears bands (ASPINWALL et al., 2003) and work-harden during machining. Additionally, their high strength maintained at elevated temperature and their low modulus of elasticity further impair their machinability. These pose considerable problems in manufacturing hence titanium-alloys have poor machinability (MILLER (1996), EZUGWU; WANG (1997), VIGNEAU (1997), GATTO; IULIANO (1997)). The poor machinability of titanium alloys have prompted many large companies (e.g. Rolls-Royce and General Electrics) to invest large sums of money in developing techniques to minimise machining and overall processing costs (EZUGWU; WANG, 1997). The best tool material is one that will maximise the efficiency and ensure accuracy at the lowest cost, in other words, one that will satisfy the requirements of a specific workpiece material (OKEKE, 1999). A cutting tool must possess high resistance to abrasion in order to withstand changes in dimensions by rubbing action; hot-hardness to maintain a sharp and consistent cutting edge when machining at elevated temperature conditions; chemical stability (lack of affinity between the tool and workpiece) in order to avoid the formation of a built-up edge; high resistance to thermal shock in order to withstand continuous heating and cooling cycles (typical in milling operation) and high toughness which allows the insert to absorb the forces and shock loads during machining. If a machine tool is not sufficiently tough, then induced shock load alone can cause the edge to chatter.

Despite the developments in cutting tool materials for the machining of difficult-to-machine materials at higher metal removal rates, they tend to be ineffective in machining titanium-alloys because of their high chemical affinity. Also, recent developments in coating technology seem to demonstrate only marginal improvement when machining titanium-alloys, despite additional cost of the coated inserts. Ceramics and Cubic Boron Nitride (CBN)/Polycrystalline Cubic Boron Nitride (PCBN) tools are not usually recommended for machining titanium-alloys because of their poor performance due to excessive wear rates as a result of the high reactivity of titanium-alloys to the tool materials in addition to their relatively high cost (HONG; MARKUS; JEONG, 2001). Cutting tools used for machining titanium alloys generally exhibit accelerated wear as a result of extreme thermal and mechanical stresses close to the cutting edge. An ideal cutting tool for machining titanium should have, among others, a hot hardness property to withstand elevated temperatures generated at relatively high speed conditions. Reduction of hot hardness at elevated temperature conditions lead to the weakening of the inter-particle bond strength and the consequent acceleration of tool wear. In addition to that, the machining environment plays a very important role in order to improve the machinability of titanium alloys.

Aero-engine alloys, particularly titanium alloys, cannot be effectively machined without cooling. There is excessive concentration of temperature at the cutting interfaces when machining titanium alloys because of their poor thermal conductivity. In addition to that, practically all the energy consumed in machining is converted into thermal energy. Cutting fluids are used to minimise problems associated with the high temperature and high stresses generated at the cutting edge of the tool during machining. Titanium alloys are generally machined using conventional coolant flow. Also, there is other technique to deliver coolant in variable quantities at high/ultra high pressures, generally within the range 0.5 – 360 MPa (SECO TOOLS (2002a)). This technique has been employed when machining mainly nickel alloys. One of the benefits of using high pressure coolant supply is because it acts as a chip-breaker. Additionally, the temperature gradient is reduced by penetration of the high-energy jet into the tool-chip interface and consequently eliminating the seizure effect (MAZURKIEWICZ; KUBALA; CHOW, 1989), thereby providing adequate lubrication at the tool-chip interface with a significant reduction in friction (EZUGWU; BONNEY; YAMANE, 2003). These combined with high velocity coolant flow causes the breakage of the continuous-type chips into very small segments. Because the tool-chip contact time is shorter, the tool is less susceptible to dissolution wear caused by chemical reaction with newly generated chips, especially titanium-alloy chips (LINDEKE; SCHOENIG; KHAN, 1991). Increase in productivity has been noticed using high pressure coolant delivery relative to the conventional methods of coolant delivery when machining nickel and titanium alloys at lower speed conditions. Other cooling technique like the minimum quantity of lubrication (MQL) has shown considerably improvement in the machinability of aerospace alloys compared to conventional coolant flow and looks promising for machining titanium alloys in order to improve the tribological processes present at the tool-workpiece interface and at the same time eliminate environmental damages as well as minimizing some serious problems regarding the health and safety of operators (SOKOVIC; MIJANOVIC (2001), DA SILVA; BIANCHI (2000), LI et al. (2000), MACHADO; WALLBANK (1997)). With the same purpose other environments such as atmospheric air (dry machining), argon enriched environment and liquid nitrogen (cryogenic machining) are also been employed as alternative cooling technology to improve the machinability of titanium-alloys. Since the gases can alter the tribological conditions existing between two surfaces in contact such as the cutting zone during machining, other environments such as atmospheres, dried air, oxygen, nitrogen, CO_2 and organic compounds such as tetrachloromethane (CCl_4) and ethanol vapour (C_2H_5OH) are also expected to improve the machinability of titanium-alloys. Some special machining techniques including specially designed ledge tools, self-propelled rotary tool (SPRT), ramping technique (taper turning) and hot machining have shown remarkable success in when machining titanium alloys (EZUGWU; BONNEY; YAMANE (2003), EZUGWU; WANG (1997), EZUGWU (2005)).

This thesis on the machining Ti-6Al-4V alloy with various cutting tools and different cooling environments was developed in collaborative program with industrial partners: Rolls-Royce Plc (aero-engine manufacturer), SECO Tools (cutting tool manufacturer) and Pumps and Equipment Ltd (Warwick) who provided the high-pressure coolant delivery system for this study. A comprehensive literature survey on the machinability of aero-engine alloys under various cutting environments as well as the experimental techniques adopted in all stages of the research programme such as turning tests, data acquisition, sample preparation, analysis of the worn tools and machined surfaces, as well as initial machining results are presented in this thesis. An investigation of the machinability of components manufactured with titanium-base, Ti-6Al-4V (or IMI 318), alloy will involve the following:

i) Evaluation of recently developed cutting tools materials (uncoated and coated cemented carbides, Polycrystalline Diamond (PCD) inserts, Cubic Boron Nitride (CBN) and SiC Whiskers Reinforced Al_2O_3 Ceramics) when machining titanium-base, Ti-6Al-4V, alloy at high speed conditions;

ii) Cutting environments (high pressure coolant supplies at pressures of 7 MPa (70 bar), 11 MPa (110 bar) and 20.3 MPa (203 bar), argon enriched environment, and conventional coolant flow;

iii) Validation of the optimum machining conditions achieved on prototype component without compromising its integrity.

1.1 Aims of the thesis

This thesis is geared primarily to achieve a step increase in the machining productivity of a commercially available titanium-base, Ti-6Al-4V, alloy using recently developed cutting tool materials, machining techniques and various cooling media such as conventional coolant flow, high pressure coolant supplies and argon enriched environment. This study is part of the Joint Strike Fighter (JSF) project – a vectored thrust, multi-role combat aircraft designed for conventional take-off and landing or a Navy version which requires Short Take Off/Vertical Landing capability in collaboration with Rolls-Royce plc. The thesis aims primarily towards significant reduction in cost of manufacturing jet engines in the immediate future using modern cutting tool technology and machining techniques.

The literature survey section covers cutting tool materials and the various cutting environments employed in the machining of aero-engine alloys. The objectives of this thesis are listed below:

- Investigation of the effect of various cooling media (high-pressure coolant supply, argon enriched environment and conventional coolant flow) on tool performance when finish turning of titanium-base, Ti-6Al-4V (IMI 318), alloy;
- Investigation of the dominant tool failure modes and wear mechanisms of newly developed cutting tools (uncoated and coated cemented carbides, different grades of Polycrystalline Diamond (PCD), Cubic Boron Nitride (CBN), SiC Whiskers Reinforced Ceramic, and Al_2O_3 and Si_3N_4 base nano-grain ceramic inserts) when finish turning of titanium-base, Ti-6Al-4V (IMI 318), alloy at high speed machining;

- Analysis of the surface finish and surface integrity of machined surfaces as well as run-out of the machined bars;
- Selection of the best combination of cutting tool-cutting environment-cutting conditions to employ in the machining of prototypes/scaled down models of the 3 bearing swivel nozzle.