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REVIEW ON MACHINING OF TITANIUM AND ALLOYS USED IN HUMAN IMPLANTS /BIOMECHANISMS + AEROSPACE INDUSTRIES

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ABSTRACT

The Major applications of Titanium are in advanced industrial production process such as in aeronautics, medical implants, automotive and power generation systems because of the excellent properties such as high strength and corrosion resistance at high temperatures. The tool wears increases rapidly due to low thermal conductivity of titanium which increases the production and running cost of the process.The paper discuss about titanium which has been perceived as a material that is difficult to machine. Due to titanium's growing acceptance in many industries, along with the experience gained by fabricators, a broad base of titanium knowledge now exists. Machining of titanium alloys requires cutting forces only slightly higher than those needed to machine steel, but these alloys have metallurgical characteristics that make them somewhat more difficult to machine than steels of equivalent hardness.

I. INTRODUCTION

1.1 History of titanium

Titanium is a chemical element with symbol **Ti** and atomic number 22. It is a lustrous transition metal with a silver color, low density and high strength. It is highly resistant to corrosion in sea water, aqua regia and chlorine.Titanium can be alloyed with iron, aluminum, vanadium, and molybdenum, among other elements, to produce strong, lightweight alloys for aerospace (jet engines, missiles, and spacecraft), military, industrial process (chemicals and petro-chemicals, desalination plants, pulp, and paper), automotive, agri-food, medical prostheses, orthopedic implants, dental and endodontic instruments and files, dental implants, sporting goods, jewelry, mobile phones, and other applications.The two most useful properties of the metal are corrosion resistance and the highest strength-to-density ratio of any metallic element. In its unalloyed condition, titanium is as strong as some steels, but less dense. There are two allotropic formsand five naturally occurring isotopes of this element, ^{46}Ti through ^{50}Ti, with ^{48}Ti being the most abundant (73.8%). Although they have the same number of valence electrons and are in the same group in the periodic table, titanium and zirconium differ in many chemical and physical properties

The fact that titanium sometimes is classified as difficult to machine by traditional methods in partcan be explained by the physical, chemical andmechanical properties of the metal. For example:

- Titanium is a poor conductor of heat. Heat,generated by the cutting action, does notdissipate quickly. Therefore, most of the heatis concentrated on the cutting edge and thetool face.
- Titanium has a strong alloying tendency orchemical reactivity with materials in thecutting tools at tool operating temperatures.This causes galling, welding and smearingalong with rapid destruction of the cuttingtool.

• Titanium has a low modulus of elasticity, thusit is more “springy” than steel. This meansthat the work-piece tends to move away fromthe cutting tool unless heavy cuts aremaintained. Slender parts tend to deflectunder tool pressure and this can causechatter, tool rubbing and hence toleranceproblems. Rigidity of the entire machiningsystem is consequently very important, as isthe use of sharp, properly shaped cuttingtools.

• Titanium’s work-hardening characteristics aresuch that titanium alloys demonstrate acomplete absence of “built-up edge”.Because of the lack of a stationary mass ofmetal (BUE) ahead of the cutting tool, a highshearing angle is formed. This causes a thinchip to contact a relatively small area on thecutting tool face and results in high loads perunit area. These high forces, coupled with thefriction developed by the chip as it passesover the cutting area, result in a greatincrease in heat on a very localized portion ofthe cutting tool. All this heat (which thetitanium is slow to conduct away), andpressure, means that tool life can be short,especially as titanium has a tendency to gallWhen cutting titanium, as cutting speedincreases, tool life dramatically decreases, forreasons out-lined above.Thus, although the basic machining properties oftitanium metal cannot be altered, their effects canbe greatly minimized by decreasing temperaturesgenerated at the tool face and cutting edge if thefollowing rules are observed:

• Use low cutting speeds. Tool tiptemperatures are affected more by cuttingspeed than by any other single variable. (Achange from 20 to 150 sfpm with carbidetools results in a temperature change fromabout 800°F to 1700°F).• Maintain high feed rates. Temperature is notaffected by feed rate nearly so much as byspeed, thus the highest feed rates consistentwith good machining practice should be used.Note: a change from 0.002” to 0.02” perrevolution (a 10 fold increase) results in atemp increase of only about 300°F. (Comparethis to the temperature increase resultingfrom only a seven and one half fold increasein cutting speed- 900°F).• Use generous amounts of cutting fluid.Coolant carries away heat, washes awaychips, and reduces cutting forces.• Use sharp tools and replace them at the firstsign of wear. However, note that tool wear isnot linear when cutting titanium. Completetool failure occurs rather quickly after a smallinitial amount of wear takes place.• Never stop feeding when a tool and workpieceare in moving contact. Permitting a toolto dwell in a moving contact causes workhardening and promotes smearing, galling,seizing and total tool breakdown.Applications;-

Machining of Titanium:- The various processes used for conventional machining of titanium are given below

1. Turning
2. Drilling
3. Milling
4. Chemical Milling
5. Reaming
6. Broaching
7. Tapping

1.2 Machining of Titanium

Machining of titanium on conventional equipment is considered by experienced operators as being no more difficult than the machining of austenitic stainless steel. Different grades of titanium varying from commercially pure to complex alloys do have different machining characteristics as do different grades of steel or different aluminum alloys. However, provided the following measures are given due consideration, little difficulty should be experienced.

- **Turning**

Disposable carbide tools should be used whenever possible for turning and boring since they increase the production rates. Where high speed steel tools must be used, such as drilling, super grades like T-15 are recommended. Overhang should be kept to a minimum in all cases to avoid deflection and reduce the tendency for titanium to smear on the tool flank.

- **Drilling**

High speed drills are satisfactory for the lower hardness commercially pure grades but super-high-speed steels or carbide should be used for the harder alloy grades and for deep holes. Sharp, clean drills just long enough for the hole being drilled and of sufficient length to allow a free flow of chips should be used. A dull drill impedes the flow of chips along the flutes and is indicated by the feathered or discolored chips. Cutting and chip clearance can be improved by spiral point drills, rather than chisel edge. Spiral points reduce the large negative rake angle of the chisel edge drill, provide a proper clearance angle along the entire cutting edge and reduce thrust loading significantly.

- **Milling**

When facing, ‘climb milling’ should be used to lengthen the life of face milling cutters. Climb milling produced a thing chip as the cutter teeth leave the work reducing the tendency of the chip to weld to the cutting edge. Relief or clearance angles for face milling cutters should be greater than those used for steel. Sharp tools must be used. End milling of titanium is best performed using short length cutters. Cutters should have sufficient flute space to prevent chip clogging. Cutters up to 25 mm (1in) diameter should have no more than 3 flutes.

- **Chemical Milling**

Very precise intricate milling or titanium can be effected by using controlled selective acid attack of the surface. The titanium component is placed in a solution of 12-20% nitric acid and 4-5% hydrofluoric acid with a wetting agent. Solution temperature is maintained between 30-40°C (86-105°F). At 36°C (95°F) metal is removed at a rate of 0.02mm/min (0.08thou/min). Areas which do not require material removal are masked with either neoprene elastomer or isobutylene-isoprene co-polymer.

- **Reaming**

Holes drilled or bored for the reaming of titanium should be 0.25-0.50mm (0.01-0.02in) undersize. Standard high speed steel and carbide reamers are satisfactory. The clearance on the chamfer should be at least 10°. Reamers with a minimum number of flutes for a given size should be selected to provide maximum tooth space for chip clearance.

- **Broaching**

It is recommended that broach tools be wet ground to improve tool finish and give better tool performance. Vapor blasting with coolant during broaching lengthens tool life and reduces the tendency to smear. Broach and broach slots should be regularly inspected for signs of smearing and chip welding as these are indications of wear.

- **Tapping**

Straight, clean holes must be drilled to ensure good tapping. Reducing the tendency of titanium to smear to the lands of the tap by nitriding the taps, relieving the land, use of an interrupted tap or providing for a free flow of chips in the flutes will ensure sound threads are produced. Chip clogging can be reduced by the use of spiral pointed taps, which push the chips ahead of the tool and give more chip clearance can be provided by sharply grinding away the training edges of the flutes. For correct clearance, two fluted spiral point taps are recommended for diameters up to 8mm (0.3in) and three fluted taps for larger sizes.

1. Application of Titanium in medical implants and instruments are listed below:-

- Suitability of Titanium for Implant Purposes
- Titanium Performance in Medical Applications
- Titanium Medical Specifications
- Bone and Joint Replacement
- Dental Implants
- Maxillofacial and Craniofacial Treatments
- Cardiovascular Devices
- External Prostheses
- Surgical Instruments

The high strength, low weight, outstanding corrosion resistance possessed by titanium and titanium alloys have led to a wide and diversified range of successful applications which demand high levels of reliable performance in surgery and medicine as well as in aerospace, automotive, chemical plant, power generation, oil and gas extraction, sports, and other major industries.

1.3 Suitability of Titanium for Implant Purposes

More than 1000 tonnes (2.2 million pounds) of titanium devices of every description and function are implanted in patients worldwide every year. Requirements for joint replacement continue to grow as people live longer or damage themselves more through hard sports play or jogging, or are seriously injured in road traffic and other accidents. Light, strong and totally biocompatible, titanium is one of few materials that naturally match the requirements for implantation in the human body

Medical grade titanium alloys have a significantly higher strength to weight ratio than competing stainless steels. The range of available titanium alloys enables medical specialists designers to select materials and forms closely tailored to the needs of the application. The full range of alloys reaches from high ductility commercially pure titanium used where extreme formability is essential, to fully heat treatable alloys with strength above 1300 MPa, (190ksi). Shape-memory alloys based on titanium, further extend the range of useful properties and applications. A combination of forging or casting, machining and fabrication are the process routes used for medical products. Surface engineering frequently plays a significant role, extending the performance of titanium several times beyond its natural capability.

1.4 Titanium Performance in Medical Applications

'Fit and forget', is an essential requirement where equipment in critical applications, once installed, cannot readily be maintained or replaced. There is no more challenging use in this respect than implants in the human body. Here, the effectiveness and reliability of implants, and medical and surgical instruments and devices is an essential factor in saving lives and in the long term relief of suffering and pain. Implantation represents a potential assault on the chemical, physiological and mechanical structure of the human body. There is nothing comparable to a metallic implant in living tissue. Most metals in body fluids and tissue are found in stable organic complexes. Corrosion of implanted metal by body fluids, results in the release of unwanted metallic ions, with likely interference in the processes of life. Corrosion resistance is not sufficient of itself to suppress the body’s reaction to cell toxic metals or allergenic elements such as nickel, and even in very small concentrations from a minimum level of corrosion, these may initiate rejection reactions. Titanium is judged to be completely inert and immune to corrosion by all body fluids and tissue, and is thus wholly bio-compatible.

The natural selection of titanium for implantation is determined by a combination of most favourable characteristics including immunity to corrosion, bio-compatibility, strength, low modulus and density and the capacity for joining with bone and other tissue - osseointegration. The mechanical and physical properties of titanium alloys combine to provide implants which are highly damage tolerant. The human anatomy naturally limits the shape and allowable volume of implants. The lower modulus of titanium alloys compared to steel is a positive factor in reducing bone resorbtion. Two further parameters define the usefulness of the implantable alloy, the notch sensitivity, - the ratio of tensile strength in the notched vs un-notched condition, and the resistance to crack propagation, or fracture toughness. Titanium scores well in both cases. Typical NS/TS ratios for titanium and its alloys are 1.4 - 1.7 (1.1 is a minimum for an acceptable implant material). Fracture toughness of all high strength implantable alloys is above 50MPa.m-½ with critical crack lengths well above the minimum for detection by standard methods of non-destructive testing.

1.5 Bone and Joint Replacement

About one million patients worldwide are treated annually for total replacement of arthritic hips and knee joints.The prostheses come in many shapes and sizes. Hip joints normally have a metallic femoral stem and head which locates into an ultrahigh molecular weight low friction polyethylene socket, both secured in position with polymethyl methacrylate bone cement. Some designs, including cementless joints, use roughened bioactive surfaces (including hydroxyapatite) to stimulate osseointegration, limit resorption and thus increase the implant lifetime for younger recipients. Internal and external bone-fracture fixation provides a further major application for titanium as spinal fusion devices, pins, bone-plates, screws, intramedullary nails, and external fixators.

1.6 Dental Implants

A major change in restorative dental practice worldwide has been possible through the use of titanium implants. A titanium ‘root’ is introduced into the jaw bone with time subsequently allowed for osseointegration. The superstructure of the tooth is then built onto the implant to give an effective replacement.

1.7 Maxillofacial and Craniofacial Treatments

Surgery to repair facial damage using the patients own tissue cannot always obtain the desired results. Artificial parts may be required to restore the ability to speak or eat as well as for cosmetic appearance, to replace facial features lost through damage or disease. Osseo integrated titanium implants meeting all the requirements of biocompatibility and strength have made possible unprecedented advances in surgery, for the successful treatment of patients with large defects and hitherto highly problematic conditions.

1.8 Cardiovascular Devices

Titanium is regularly used for pacemaker cases and defibrillators, as the carrier structure for replacement heart valves, and for intra-vascular stents.

1.9 External Prostheses

Titanium is suitable for both temporary and long term external fixations and devices as well as for orthotic callipers and artificial limbs, both of which use titanium extensively for its light weight, toughness and corrosion resistance.

1.10 Surgical Instruments

A wide range of surgical instruments are made in titanium. The metal's lightness is a positive aid to reducing any fatigue of the surgeon. Instruments are frequently anodized to provide a non reflecting surface, essential in microsurgical operations, for example in eye surgery. Titanium instruments withstand repeat sterilisation without compromise to edge or surface quality, corrosion resistance or strength. Titanium is non magnetic, and there is therefore no threat of damage to small and sensitive implanted electronic devices.

2. Titanium Alloys for Aero engine and Airframe Applications

a) Aircraft Engines

b) Airframes

c) Titanium Alloys for Aircraft Applications

The high strength and low density of titanium and its alloys have from the first ensured a positive role for the metal in aero-engine and airframe applications. It is difficult to imagine how current levels of performance, engine power to weight ratios, airframe strength, aircraft speed and range and other critical factors could be achieved without titanium.

1.11 Aircraft Engines

Titanium alloys capable of operating at temperatures from subzero to 600°C are used in engines for discs, blades, shafts and casings from the front fan to the last stage of the high pressure compressor, and at the rear end of the engine for lightly loaded fabrications such as plug and nozzle assemblies.

- **Airframe**

Alloys with strength up to 1200MPa are used in a wide variety of airframe applications from small fasteners weighing a few grams to landing gear trucks and large wing beams weighing up to 1 ton. Currently titanium makes up to 10% of empty weight of aircraft such as the Boeing 777.

- **Titanium Alloys for Aircraft Applications**

Some of the alloys available for aircraft applications are outlined in the following tables. The alloys are grouped by their relative usages.

II. LITERATURE REVIEW

2.1 Classification of titanium alloys

Titanium alloys may be divided into four main groups, according to their basic metallurgical characteristics: e alloys, near e alloys, e-flalloys and alloys [12 3 4].

- **e alloys:**

These contain ~-stabilisers, sometimes in combination with neutral elements, and hence have an ephase microstructure. The alloy has excellent tensile properties and creep stability at room and elevated temperatures up to 300°C. a-alloys are used chiefly for corrosion resistance and cryogenic applications.

- **Near e alloys:**

These alloys are highly e-stabilised and contain only limited quantities of fl-stabilising elements. They are characterized by a microstructure consisting of c~ phase containing only small quantities of fl phase.

- **e-fl alloys**:

This group of alloys contains addition of .e- and fl-stabilisers and they possess microstructures consisting of mixtures of e- and /3-phases. They can be heat-treated to high strength levels and hence are used chiefly for high-strength applications at elevated temperatures of between 350 and 400°C.

- **fl alloys:**

These alloys contain significant quantities of/3-stabilisers and are characterised by high hardenability, improved forgeability and cold formability, as well as high density. Basically, these alloys offer an ambient temperature strength equivalent to that of e-B alloys, but their elevted temperature properties are inferior to those of the e-fl alloys. As far as the gas turbine engine is concerned, the most important alloys are those in the near and e-/3 groups, the ct-/3 alloy [5].

2.2 Machining of titanium alloys

C.-F. Wyen, K. Wegener [6] has investigated orthogonal turning tests on Ti–6Al–4V with different cutting edge radii and changing cutting speeds and feeds. As an accurate characterization method for the determination of the cutting edge radius is prerequisite for this analysis, a new algorithm is described which reduces uncertainties of existing methods. They had concluded a method for the characterization of rounded cutting edges isintroduced, which effectively reduces uncertainties of availablemethods and enables a unique determination of the dimension of acutting edge radius.Active force components including ploughing force have beendetermined for different cutting edge radii in orthogonal turning ofTi–6Al–4V. Feed forces react more sensitive to a change in cuttingedge radius than cutting forces. Ploughing forces can significantlycontribute to the total forces in a cutting process. The experimentaldata indicate that in machining titanium ploughing forces existeven for ideal sharp tools. The coefficient of friction is found to beinfluenced by both cutting edge radius and cutting speed. Theinfluence of cutting speed on feed force is non-linear and dependson the cutting edge radius.

Y. Ayeda, *et al*[7] had investigated the influence of the cutting speed and the water jet pressure on the evolution of tool wear and cutting forces. The cutting speed has been varied between 50 m/min and 100 m/min and the water jet pressure has been varied from 50 bar to 250 bar. The optimum water jet pressure has been determined, leading to an increase in tool life of approximately 9 times. Compared to conventional lubrication, an increase of about 30% in productivity can be obtained. They had concluded that certain value of the axial forcepresents a sign of flank wear (0.3 mm).It has been remarked that, for pressures beyond 100 bar,scratches on the surface of the work piece have been noticed.Moreover, welded fragments of chips have been observed on themachined surface, which can be the result of chips recycling phenomenon.

S. Basturk*et al*[8] had studied Titanium is a commonly used material in various critical applications such as aerospace and biomedical applications. In this paperthey had implemented a novelplasma boronizing process on Tungsten Carbide (WC) cutting tools. Plasma boronizing on WC tools was performed with gas combination of 10% BF3, 40% Argon and 50% H2 at different temperaturesand durations. Performance enhancements of plasma boronized WC tools on Titanium (Ti–6Al–4V)machining are investigated under various cutting conditions. They found that new plasma boronizing ofWC is a very cost effective solution for significantly increasing tool life in Titanium machining.It was observed that plasma boronized tools help to lower thecutting forces slightly. More importantly, plasma boronizingprocess increases tool cost less than 5%, while it helps to increasethe WC tool life triple.

BerendDenkena*et al*[9] had concluded that machining of titanium alloys has a correlation between process power and cutting fluid.Furthermore, it was shown that optimized cutting parameters lead to energy savings of more than 40 percent at the working spindle. The improvement of the energy efficiency of titanium machining is generally possible without impairing productivity. Energy savings at the spindle motor of up to 48% are achieved by a selective choice of process parameters generating the same material removal rate.

D.A. Dornfeldl*et al*[10] had studied that Titanium alloy (Ti-6AI-4V) plates were drilled to investigate the effects of tool geometry as well as processconditions on the drilling burr formation. Drilling was done with solid carbide tools with and without coolant andhigh speed cobalt drills without coolant. Four distinct burr types were observed. During dry cutting, a “rolledback” type burr was observed at high feed rates and cutting speeds and is believed to be due to thermaleffects. A “ring” type burr was observed when drilling with coolant. While cutting conditions had little effect onthe burr sizes formed, drill geometry (helix angle, split point vs. helical point, lip relief angle and point angle)affected burr thickness and height.Geometry of the drill greatly affects burr formation:Helical point drill produced smaller burrs than splitpoint drill: Larger helix angle and increasing pointangle both reduced burr height and thickness.

Progress in the machining of titanium alloys has notkept pace with advances in the machining of othermaterials due to their high temperature strength, verylow thermal conductivity, relatively low modulus ofelasticity and high chemical reactivity. Therefore, successin the machining of titanium alloys depends largelyon the overcoming of the principal problems associatedwith the inherent properties of these materials, as discussedbelow:

- **High cutting Temperature**

It is well known that high cutting temperatures aregenerated when machining titanium alloys and thefact that the high temperatures act close to thecutting edge of the tool are the principal reasons forthe rapid tool wear commonly observed. A large proportion (about 80%) ofthe heat generated when machining titanium alloyTi-6AI-4V is conducted into the tool because itcannot be removed with the fast flowing chip or bedinto the work piece due to the low thermal conductivityof titanium alloys, which is about 1/6 that ofsteels [11,12]. About 50% of the" heat generated isabsorbed into the tool when machining steel. Investigationof the distribution of the cutting temperature

has shown that the temperature gradients are muchsteeper and the heat-affected zone much smaller andmuch closer to the cutting edge when machiningtitanium alloys because of the thinner chips produced(hence short chip-tool contact length) and the presenceof a very thin flow zone between the chip andthe tool (approximately

8 ~tm compared with 50 lamwhen cutting iron under the same cutting conditions)which causes high tool-tip temperatures of up toabout 1100°C [23-27].

- **High cutting pressures:**

The cutting forces recorded when machining titaniumalloys are reported to be similar to those obtainedwhen machining steels [13], thus the power consumptionduring machining is approximately the same orlower [14]. Much higher mechanical stressesdo, however, occur in the immediate vicinity of thecutting edge when machining titanium alloy. Konig[11] has reported higher stresses on the tool whenmachining Ti-6AI-4V (titanium alloy) than whenmachining Nimonic 105 (nickel-based alloy) andthree to four times those observed when machiningsteel Ck 53N (Fig. 2). This may be attributed to theunusually small chip-tool contact area on the rakeface, (which is about one-third that of the contactarea for steel at the same feed rate and depth of cut)[15] and partly to the high resistance of Ti-aUoy todeformation at elevated temperatures, which onlyreduces considerably at temperatures in excess of800°C [11,16].

- **Chatter:**

Chatter is another main problem to be overcomewhen machining titanium alloys, especially for finishmachining, the low modulus of elasticity of titaniumalloys being a principal cause of the chatter duringmachining. When subjected to cutting pressure, titaniumdeflects nearly twice as much as carbon steelthe greater spring-back behind the cutting edge resultingin premature flank wear. vibration and highercutting temperature [16]. In effect, there is a bouncingaction as the cutting edge enters the cut. Theappearance of chatter may also be partly ascribed tothe high dynamic cutting forces in the machining oftitanium. This can be up to 30% of the value of thestatic forces [11] due to the 'adiabatic or catastrophicthermoplastic shear' process by which titanium chipsare formed [17,18].

III. CONCLUSION

Titanium and its alloys are considered as difficultto-cut materials due to the high cutting temperatureand the high stresses at and/or close to the cutting edgeduring machining. The high cutting temperature is dueto the heat generated during machining (catastrophicthermoplastic shear process), the thin chips, a thinSecondary zone, a short chip-tool contact length andthe poor heat-conductivity of the metal, whilst the highstresses are due to the small contact area and thestrength of titanium even at elevated temperature.The machining methods used for titanium areessentially those that have been used since titaniumbecame used widely in the early 1960s. However, somespecial machining techniques such as the use of edgetools and rotary tools and other non-conventional machiningmethods~ may be thought of as alternativemethods to increase the metal removal rate in theproduction of titanium components, provided that thecomponent geometry integrity permits this. There is a lack of research onquantification of chemical reactivitybetween titaniumand tool material, and on the relationship betweencutting parameters and work piece hardening.Mostof the investigations carried out on themachinabilityof titanium alloys were based on different cuttingconditions, whichmake it difficult to compare resultsfromdifferent authors.

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