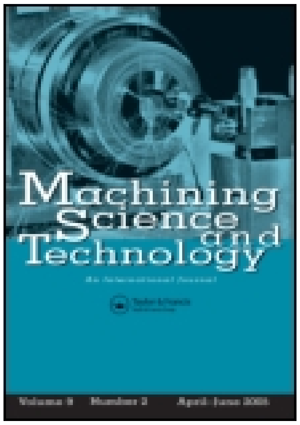

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MACHINING TITANIUM AND ITS ALLOYS

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REVIEW ARTICLE

MACHINING TITANIUM AND ITS ALLOYS

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ABSTRACT

Titanium and its alloys are attractive materials due to their unique high strength-weight ratio that is maintained at elevated temperatures and their exceptional corrosion resistance. The major application of titanium has been in the aerospace industry. However, the focus shift of market trends from military to commercial and aerospace to industry has also been reported. On the other hand, titanium and its alloys are notorious for their poor thermal properties and are classified as difficult-to-machine materials. These properties limit the use of these materials especially in the commercial markets where cost is much more of a factor than in aerospace. Machining is an important manufacturing process because it is almost always involved if precision is required and is the most cost effective process for small volume production. This paper reviews the machining of titanium and its alloys and proposes potential research issues.

Keywords: Machining; Machinability; Residual Stress; Surface Integrity; Titanium.

INTRODUCTION

Titanium alloys are attractive materials due to their unique high strength-weight ratio that is maintained at elevated temperatures, and their exceptional corrosion resistance. The major application of titanium is in the aerospace industry, where it is used both in airframes and engine components. Non-aerospace applications take advantage mainly of their excellent strength properties or corrosion resistance [1,2,3]. Typical application areas include automotive, chemical/

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energy, medical, and sporting goods [4]. It has been reported that the applications of titanium to non-aerospace industry have increased [5,6]. The Ti-6Al-4V comprises about 45% to 60% of the total titanium production [2,7,8,9]. Adams [10] also reports the focus shift of market trends from military to commercial and aerospace to industrial. Initial high cost, availability, and manufacturability have limited titanium's use. Improved fabrication methods could result in reduced scrap losses and fabrication time, and thus reduced cost and increased availability [11].

A literature search reveals that the machining of titanium and its alloys have not received much attention in recent years. This may result from the difficulties associated with machining titanium and its alloys. Siekmann pointed out in 1955 that 'machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips [12]. Komanduri and Reed have commented that 'this is still true in so far as cutting tool materials are concerned' (1983) [13].

Adams [10] emphasizes the lower cost in the R&D trends and requirements for success for titanium industry. Froes et al. [9] also assert that "now the expansion of the titanium market will be even more dependent on reducing the cost." This can be achieved best if the machinability of titanium and its alloys can be improved because machining is almost always involved if precision is required and is the most cost effective process for small volume production [14].

This paper reviews the issues related to the machining of titanium and its alloys and proposes potential research issues.

METALLURGY OF TITANIUM ALLOYS

To better understand the machining of titanium and its alloys, basic knowledge on these materials is necessary. This section summarizes the information from references [2,8,9,12,15,16,17,18,19,49].

Classification of Titanium and Its Alloys

Titanium exists in two crystalline states: in a low-temperature α phase (hcp) and a high temperature β phase (bcc). The hcp structure of titanium affords a limited number of slip or shear planes. On the other hand, the bcc structure has more slip systems, thereby enabling more deformation locally wherever the structure has transformed from hcp into bcc. The allotropic transformation of pure titanium takes place around 882°C (Figure 1). By adding certain elements this temperature can be either raised or lowered. The 'α stabilizers' such as Al, O, N, Ga, and C produce an increase in the temperature. The 'β stabilizers' such as Mo, V, Ta (isomorphous formers), Cu, Cr, Fe, Mn, Ni, Co, and H (eutectoid formers) produce a decrease in temperature of transformation. The 'neutral elements' such as Sn, Si, and Zr have little influence on the transformation temperature. The classification (Figure 2) is:

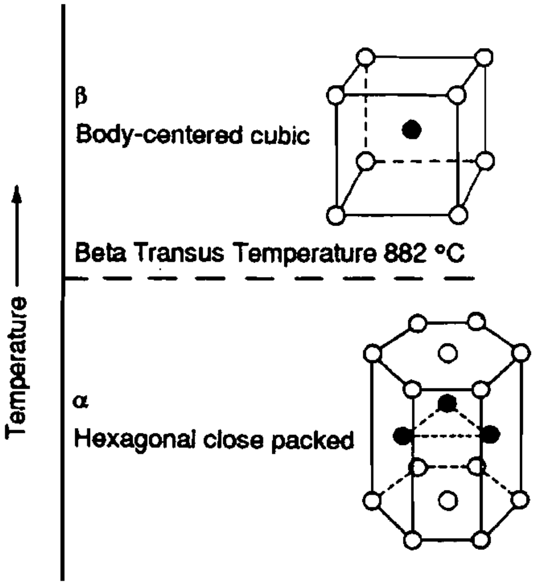


Figure 1. The two allotropic forms of titanium (after Froes et al. [9]).

- Commercially Pure (Unalloyed) Titanium: excellent corrosion resistance and low strength properties.
- α and near-α Alloys: containing α stabilizers and possessing excellent creep resistance.
- α-β Alloys: containing both α stabilizers and β stabilizers. They account for 70% of all titanium used, among which Ti-6Al-4V is the most common one comprising about 45% to 60% of the total titanium production.
- β Alloys: containing significant quantities of β stabilizers. High hardenability and a higher density.
- Titanium Aluminides, Ti_3Al (α_2) and TiAl (γ): can be used at as high as 900°C. Low room temperature ductility.

Selected Titanium Properties

Titanium has a density of 4.50 Mg/m^3, and titanium alloys have densities in the range 4.50–4.84 Mg/m^3. Table 1 is the physical and mechanical properties of elemental titanium. Table 2 is a simple comparison of selected properties between Ti-6Al-4V and AISI 1045 steel.

Table 3 is a summary of the strength of commercial and semicommercial grades and alloys of titanium.

Table 4 illustrates the technical advantages that resulted from the introduction of titanium in the JT-3 gas turbine.

Figure 3 is a comparison of strength-density behavior of two titanium alloys vs that of three steels as a function of temperature.

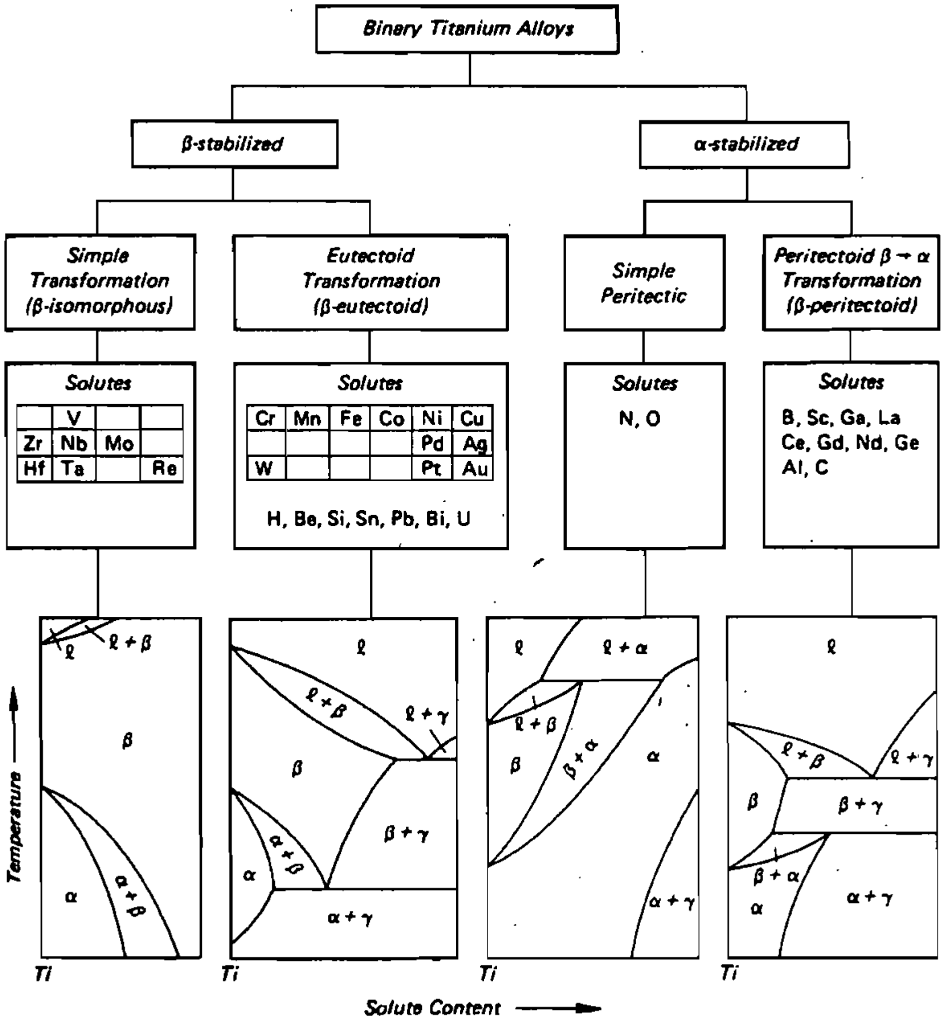


Figure 2. Classification scheme for binary titanium alloys (after Froes et al. [9]).

MACHINABILITY OF TITANIUM AND ITS ALLOYS

Webster [68] defines "machinability" as "the quality or state of being machinable"; "machinable" is defined as "capable of or suitable for being machined"; and to "machine" is defined as "to turn, shape, plane, mill, or otherwise reduce or finish by machine-operated tools." In general, there are three main aspects of machinability [20]: tool life, surface finish, and power required to cut. In addition, the chip form/chip breakability and part accuracy are also used in an assessment of machinability.

Under normal circumstances the best criterion for rating machinability is machining cost per part. Under special conditions where machine capacity is lim-

Table 1. Physical and Mechanical Properties of Elemental Titanium (after Froes et al. [9])

Atomic number	22
Atomic weight	47.90
Atomic volume	10.6 weight/density
Covalent radius	0.132 nm
First ionization energy	661.5 MJ/(kj mol)
Thermal neutron absorption cross section	560 fm^2/atom
Crystal structure	• α: close-packed, hexagonal ≤ 1156 K • β: body-centered, cubic ≥ 1156 K
Color	Dark gray
Density	4510 kg/m^3
Melting point	1941 ± 285 K
Solidus/liquidus	1998 K
Boiling point	3533 K
Specific heat (at 298 K)	0.518 J/(kg K)
Thermal conductivity	21 W/(m K)
Heat of fusion	440 kJ/kg
Heat of vaporization	9.83 MJ/kg
Specific gravity	4.5
Hardness	HRB 70 to 74
Tensile strength	241 GPa
Modulus of elasticity	102.7 GPa
Young's modulus of elasticity	102.7 GPa
Poisson's ratio	0.41
Coefficient of friction	0.8 at 40 m/min 0.68 at 300 m/min
Specific resistance	0.554 μΩm
Coefficient of thermal expansion	8.64×10^{-6} K^{-1}
Electrical conductivity	3% IACS (copper 100%)
Electrical resistivity	0.478 μΩm
Electronegativity	1.5 Pauling's
Temperature coefficient of electrical resistance	0.0026 K^{-1}
Magnetic susceptibility	1.25×10^{-6} emu/g
Machinability rating	40 (equivalent to $^{3}/_{4}$ hardness stainless steel)

ited and production output is of major concern, the proper machinability criterion is the number of parts per unit time [21].

Table 5 shows that power requirements of cutting titanium alloys are lower than those of cutting steels and Nickle and Cobalt Base Alloys [22]. This result is in agreement with the finding of Motonishi et al. [30] who state that no definite relation between cutting force and hardness and tensile strength of the titanium materials exists and conclude that it can hardly be said that the magnitude of cutting force causes difficulty in cutting. However, the machinability of titanium and its alloys is poor in terms of tool life. The tool wears fast and the cutting speed must be kept low, which give rise to high machining cost per part. Table 6 shows some machining time ratios for various types of titanium alloys compared to AISI 4340 steel at 300 BHN. Similarly, Catt and Milwain [33] observe that it

Table 2. Properties of Ti-6Al-4V Compared to a Medium Carbon Steel (adapted from Machado and Wallbank [2])

MATERIAL	YIELD STRENGTH (Mpa)	ELONGATION (%)	MODULUS OF ELASTICITY TENSION (Gpa)	DENSITY (g/cm^3)	STRENGTH-WEIGHT RATIO	SPECIFIC HEAT AT 20 − 100°C J/kg · K	VOLUMETRIC SPECIFIC HEAT ($J/K \cdot cm^3$)	THERMAL CONDUCTIVITY (W/m · K)
Ti-6Al-4V annealed bar	825	10	110	4.43	186.2	580	2.57	7.3
Ti-6Al-4V solution treated aged bar	965	8	—	—	—	—	—	7.5
AISI-1045 cold drawn	530	12	207	7.84	67.6	486	3.81	50.7

Table 3. Strength of Commercial and Semicommercial Grades and Alloys of Titanium (after Donachie [8])

DESIGNATION	TENSILE STRENGTH (MPa)	0.2% YIELD STRENGTH (min) (MPa)
Unalloyed grades		
ASTM Grade 1	240	170
ASTM Grade 2	340	280
ASTM Grade 3	450	380
ASTM Grade 4	550	480
ASTM Grade 7	340	280
α and near-α alloys		
Ti Code 12	480	380
Ti-5Al-2.5Sn	790	760
Ti-5Al-2.5Sn-ELI	690	620
Ti-8Al-1Mo-1V	900	830
Ti-6Al-2Sn-4Zr-2Mo	900	830
Ti-6Al-2Nb-1Ta-0.8Mo	790	690
Ti-2.25Al-11Sn-5Zr-1Mo	1000	900
Ti-5Al-5Sn-2Zr-2Mo(a)	900	830
α-β alloys		
Ti-6Al-4V(b)	900	830
Ti-6Al-4V-ELI(b)	830	760
Ti-6Al-6V-2Sn(b)	1030	970
Ti-8Mn(b)	860	760
Ti-7Al-4Mo(b)	1030	970
Ti-6Al-2Sn-4Zr-6Mo(c)	1170	1100
Ti-5Al-2Sn-2Zr-2Mo-2Cr(a)(c)	1125	1055
Ti-6Al-2Sn-2Zr-2Mo-2Cr(a)(b)	1030	970
Ti-10V-2Fe-3Al(a)(c)	1170	1100
Ti-3Al-2.5V(d)	620	520
β alloys		
Ti-13V-11Cr-3Al(c)	1170	1100
Ti-8Mo-8V-2Fe-3Al(a)(c)	1170	1100
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(b)	900	830
Ti-11.5Mo-6Zr-4.5Sn(b)	690	620

(a) Semicommercial alloy: mechanical properties and composition limits subject to negotiation with suppliers. (b) Mechanical properties given for annealed condition: may be solution treated and aged to increase strength. (c) Mechanical properties given for solution treated and aged condition; alloy not normally applied in annealed condition. Properties may be sensitive to section size and processing. (d) Primarily a tubing alloy; may be cold drawn to increase strength.

Table 4. Effect of Titanium in the JT-3 Gas Turbine (Titanium Made a Fan Configuration Possible) (after Donachie [8])

	JT-3D (fan engine) vs JT-3C (no fan)
Take-off thrust	42% more
Climb thrust-SLTO	23% more
Cruise thrust	16% more
Specific fuel consumption	13% less
Specific weight	18% less

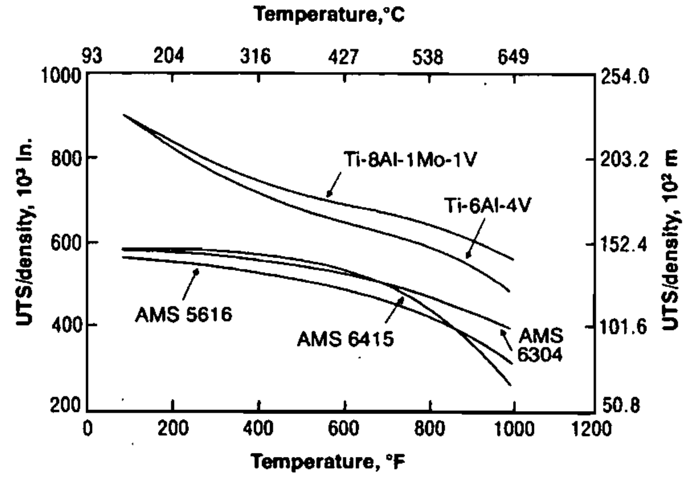


Figure 3. Strength-density behavior of two titanium alloys vs that of three steels (after Donachie [8]).

Table 5. Average Unit Power Requirements* for Turning, Drilling, and Milling (Horsepower per Cubic inch/minute) (after Kahles et al. [22])

MATERIAL	HARDNESS Bhn (3000 kg)	TURNING HSS AND CARBIDE TOOLS	DRILLING HSS DRILLS	MILLING HSS AND CARBIDE TOOLS
Steels	35–40 R_c	1.4	1.4	1.5
Titanium Alloys	250–375	1.2	1.1	1.1
High Temperature Nickel and Cobalt Alloys	200–360	2.5	2.0	2.0
Aluminum Alloys	30–150 (500 kg)	0.25	0.16	0.32

*Power requirements at spindle drive motor, corrected for 80% spindle drive efficiency. Dull tools may require 25% more power.

Table 6. Machining Time Ratios for Various Types of Titanium Alloys Compared to AISI 4340 Steel at 300 BHN (after Zlatin and Field [24])

TITANIUM ALLOY	TURNING (Carbide Tool)	FACE MILLING (Carbide Tool)	DRILLING (HSS Tool)
Commercially pure 175 BHN	0.7:1	1.4:1	0.7:1
α Ti-8Al-1Mo-1V 300 BHN	1.4:1	2.5:1	1:1
α-β Ti-6Al-4V 365 BHN	2.5:1	3.3:1	1.7:1
β Ti-13V-11Cr-3Al 400 BHN	5:1	10:1	10:1

takes over three times as long to manufacture parts from titanium as to manufacture them from aluminum alloys. It is seen from Table 6 that the hardness has a big impact on the machinability, which is also reported in Trucks [3] who claims that the machining characteristics of titanium alloys change significantly at hardness levels of 38 Rockwell (C scale). It is also seen in this Table that alloy type has an impact on the machinability. Truck [3] reports similar results. When ranked in a descending order in terms of machinability, the materials are commercially pure titanium, α alloys, α-β alloys, and β alloys.

Possible reasons for making titanium and its alloys difficult-to-cut are listed below. In addition to fast tool wear, there are problems that could cause thermal damage (e.g. items 1, 2, 3, and 7) and poor surface finish or part accuracy in cutting titanium and its alloys (e.g. items 1, 5, and 6, built-up edge at low cutting speed).

1. The poor thermal properties of the materials ([1,2,3,12,22,23,24], Table 2). This problem may be more pronounced in drilling operation using conventional twist drills because cutting speed diminishes towards the center resulting in considerable cutting forces and excessive heat [27].
2. Titanium's chip is very thin with consequently an unusually small contact area with the tool (1/3 to 1/2 of that for turning steel) [2,12,24,28], which causes high stresses on the tip of the tool. The combination of a small contact area and the low thermal conductivity results in very high cutting temperatures. The cutting speed of the titanium must be low to avoid too short tool life. The high unit pressure resulting from the thin chip, high surface friction and high heat generated could give rise to pressure welding and galling [27,29].
3. The high strength is maintained to elevated temperatures (Figure 3) that are generated in machining and this opposes the plastic deformation needed to form a chip [2].
4. High chemical affinity [1]. There is strong chemical reactivity of titanium at the cutting temperature (>500°C) with almost all tool materials available [2]. High affinity of titanium and its alloys for the interstitial oxygen and nitrogen gives rise to the pick up of interstitial of the heated outer surface layer of the workpiece during machining, which contrib-

utes partially to the hardening of titanium and its alloys in addition to the strain hardening [29]. The active properties of titanium alloys control tool wear rate (especially crater wear) [30].

5. Low modulus of elasticity (Table 2) which can cause chatter, deflection, and rubbing problems [2,12]. The forces perpendicular to the workpiece may increase three to four times as a result of a build up of titanium on the wearland of the tool (the cutting forces will generally increase 25 to 50% as the tool dulls when cutting a steel) [24]. Because of this high thrust force and the low elastic modulus of titanium, the deflection of the workpiece can be a serious problem.
6. The long stringy swarf is difficult to handle and has stymied most titanium machining automation projects [31].
7. Care must be taken about titanium's tendency to ignite during machining because of the high temperatures involved [2]. Sparks have been observed during cutting experiments in the authors' laboratory.

There are conflicting reports about machining titanium and its alloys: the ''coefficient of friction'' between the chip and the tool face is said to be high (coefficient is approximately 0.6 [29] and 1.0 [28]), but Zlatin [69] shows this to be in line with that obtained in machining many steels and Rabinowicz [32] reports that friction between titanium and the tool face is low owing to transfer of titanium to the tool face and formation of a thin oxide acting as a lubricant; even though the built-up edge is said not to occur, some authors have confirmed its presence at low cutting speeds, and this could lead to a poor surface finish in some operations [2]. However, the built-up edge could have positive impact on the machinability as well. Child and Dalton [29] claim that the absence of a built-up edge to dissipate heat leads to much higher surface heating under the tool and thereby increase the contamination of titanium and decrease tool life. Colwell and Truckenmiller [28] attempt to induce a built-up edge since the presence of it can reduce both temperature and pressure on the cutting tool; the rate of work hardening is said to be high [2], but Zlatin, Child and Dalton [29] and Trucks [3] have reported that in fact it work-hardens to a lesser extent than steel, also Shahan and Taheri [26] claim that low strain-hardening rate is one of the characteristics of $\alpha + \beta$ two-phase titanium alloys.

There are several parameters that have impact on the machinability of titanium and its alloys. In addition to the hardness and alloy type discussed above, the tool materials, lubricant, and temperature also have impact on the machinability. Hong et al. [34] conclude that overbased sodium sulfonate and calcium sulfonate showed better tapping performance than overbased magnesium sulfonate in the tapping test of 304 stainless steel and T-6Al-4V alloy. The addition of sulfurized olefin to sodium and calcium sulfonates improved the tapping efficiencies as well as the surface finish of 304 stainless steel and Ti-6Al-4V alloy. Dillon et al. [50] report that high temperature (280°C) definitively posed problems with titanium. The machinability of titanium is improved at low workpiece temperature

(−190°C). The relationship between the tool materials and tool wear in machining titanium and its alloys will be discussed in the section on Tool Wear.

Much research has been conducted to find machining conditions that give satisfactory tool lives at acceptable production rates. Recommended cutting conditions are available in Zlatin and Field [24], Catt and Milwain [33], and Trucks [3]. Note that such tool materials as CBN and diamond are not included. Other suggestions for machining titanium alloys include that the rigidity of the setup (particularly of the cutter) is especially important [24,28,33]; machine tools should be protected against the corrosive attack of otherwise favorable cutting fluids [33].

SURFACE INTEGRITY

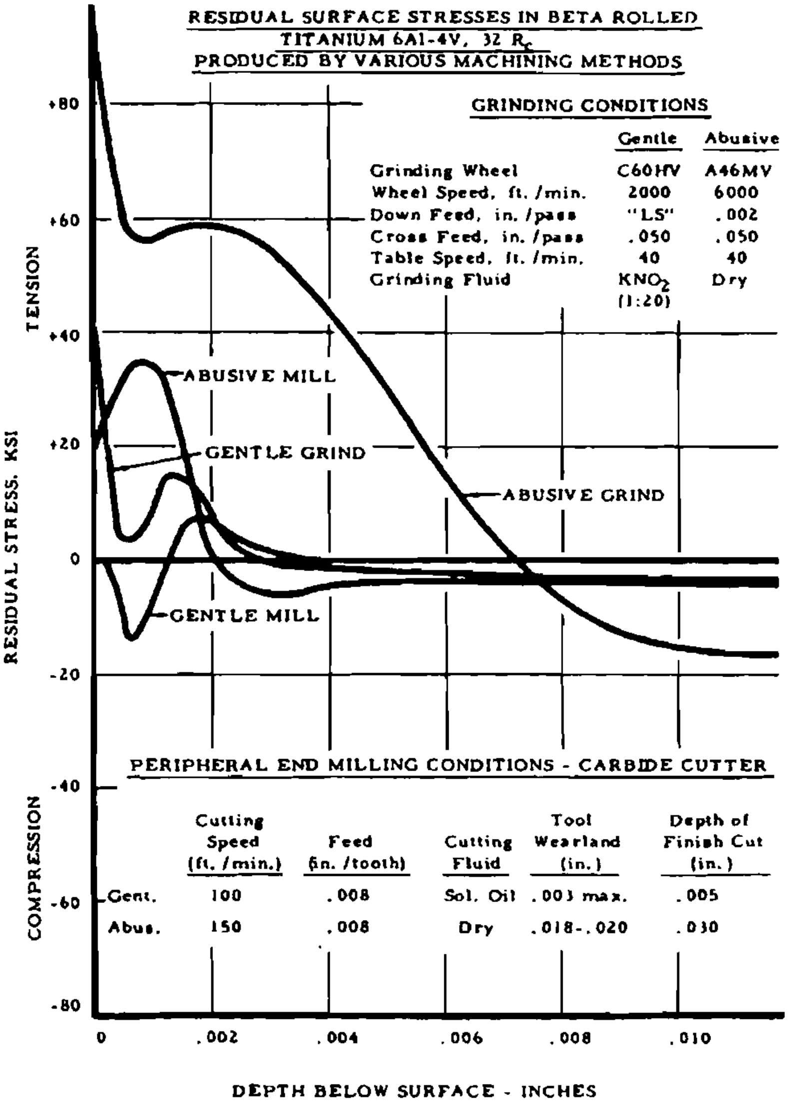
Surface integrity has been defined as the inherent or enhanced condition of a surface produced by machining [24], the parameters of which include residual stress, metallurgical alterations, and surface finish. This is an important area but has not received deserved attention. Very few attempts have been made for relating surface integrity to machining process parameters and to the performance of the machined parts.

Residual Stress and Distortion

Residual stresses are often induced in the manufacturing processes. The compressive residual stress is beneficial when fatigue strength is being considered and hence is sought after, while the tensile residual stresses should be avoided.

Machado and Wallbank [2] claim that determination of the surface residual stresses in machining titanium alloys have proved that they are compressive. However, this conclusion may only hold for certain machining conditions. Zlatin and Field [24] report that both compressive and tensile residual stresses are possible in processed titanium alloys. They use terms such as abusive and gentle in their report. In the milling operation, the major factor between the gentle and abusive milling was the tool wearland. The sharp tool with 0.003 in. maximum wearland was the predominant parameter in minimizing the residual stress. In grinding, the major factors leading to abusive grinding are hard wheel, high wheel speed, and dry grinding. EDM tends to produce a high but shallow tensile stress. ECM generally produces a surface with very little if any residual stress. See Figure 4 for their results. Yang [35] has conducted measurements of residual stresses of ground Ti-6Al-4V alloy. It is found that both compressive and tensile residual stresses are possible (Table 7). Parameters having impact on the residual stress include cutting speed, depth of cut, fluid type, coolant pressure, velocity of grinding wheel, and grit size. Table 8 is a summary of the results taken from the literature. However, little is known of the quantitative relationship between the cutting conditions and the induced residual stresses in machining titanium alloys.

High variations of residual stress on the same surface exist on ground surfaces and low variations of residual stress exist on single-point cut surfaces. The



GRINDING CONDITIONS

	Gentle	Abusive
Grinding Wheel	C60HV	A46MV
Wheel Speed, ft./min.	2000	6000
Down Feed, in./pass	"LS"	.002
Cross Feed, in./pass	.050	.050
Table Speed, ft./min.	40	40
Grinding Fluid	KNO_2 (1:20)	Dry

PERIPHERAL END MILLING CONDITIONS - CARBIDE CUTTER

	Cutting Speed (ft./min.)	Feed (in./tooth)	Cutting Fluid	Tool Wearland (in.)	Depth of Finish Cut (in.)
Gent.	100	.008	Sol. Oil	.003 max.	.005
Abus.	150	.008	Dry	.018-.020	.030

Figure 4. Every machining operation produces a distinctive residual stress in the surface layer (after Zlatin and Field [24]).

Table 7. Cutting Direction Residual Stress (Ground Sample Number 3) (after Yang [35])

SPOT NUMBER	RESIDUAL STRESS (MPa)	RESIDUAL STRESS (ksi)
1	41.3	5.949
2	−52	−7.54
3	−62	−8.99

Table 8. Cutting Parameters vs Residual Stress

	CUTTING SPEED	DEPTH OF CUT	FLUID TYPE	COOLANT PRESSURE	VELOCITY OF GRINDING WHEEL (V_s)	GRIT SIZE
Campbell [7]	—	Not important	Neat oil more compressive RS* than water-soluble	—	Higher V_s, more compressive RS	Larger size, more compressive RS
Kumagai et al. [54]	—	—	—	Higher pressure, more compressive RS	—	—
Machado & Wallbank [2]	Higher cutting speed, larger compressive RS	—	—	—	—	—
Zlatin & Field [24]	—	—	Dry grinding, RS more tensile	—	Higher V_s, RS more tensile	—
Silin et al. [70]	—	Larger DOC, Smaller RS	—	—	—	—

*RS, residual stress.

inherent differences in cutting point geometry between grinding and single-point cutting are believed to be primarily responsible for such differences [36].

Residual stresses of titanium and its alloys can be relieved by heat treatment. ASM Committee on Titanium and Titanium Alloys [37] provides recommended stress-relief treatments for titanium and its alloys. The rate of cooling from the stress-relieving temperature is not critical. Uniformity of cooling is critical, particularly in the temperature range from 480°C to 315°C. Oil or water quenching should not be used to accelerate cooling, however, because this can induce residual stresses by unequal cooling. Furnace or air cooling is acceptable. No significant changes in microstructure due to stress-relieving heat treatments can be detected by optical microscopy. Li et al. [38] study the high temperature stress relaxation of Ti-6Al-4V and give a power law formulation. Possible metallurgical changes in the microstructure and the relation between these changes and the mechanical behavior are discussed.

The distortion produced in machining is proportional to the integrated area under the residual stress curve [24].

Metallurgical Alterations

Zlatin and Field [24] report that in case of machining titanium, the possible surface alterations include plastic deformation, phase transformations, microcracking, and microhardness alterations etc. The causes of the surface alterations are high temperature or high temperature gradients, hot or cold work, and chemical reactions and subsequent absorption of products of reaction into the surface layer.

The gentle machining operations minimize surface alterations and abusive operations cause major alteration. When titanium is machined in an abusive manner, an overheated white layer can be produced which may be harder or softer than the base material [2].

Mechanical Properties

Usually, the gentle machining operations result in a high cyclic fatigue strength that is much higher (up to nearly 5 times) than that of the corresponding abusive operations (Figure 5) [24]. Kahles et al. [22] claim that the surface of titanium alloys is easily damaged during machining operations, especially during grinding. Even properly processed grinding practices using conventional parameters result in appreciably lower fatigue strength due to surface damage.

Shahan and Taheri [26] report that the shear zones hardness depends on the alloy forming conditions and the widths of the adiabatic shear zones. They could be either harder or softer than the surrounding regions. The hardness may change by as much as 100 HV in the banded microstructure. The extremely high values of the hardness in the shear band indicate a microstructural change resulting from high strain, high temperature, and rapid quenching involved in the deformation process. The high dependence of flow stress on temperature may explain small decrease in flow stress during straining.

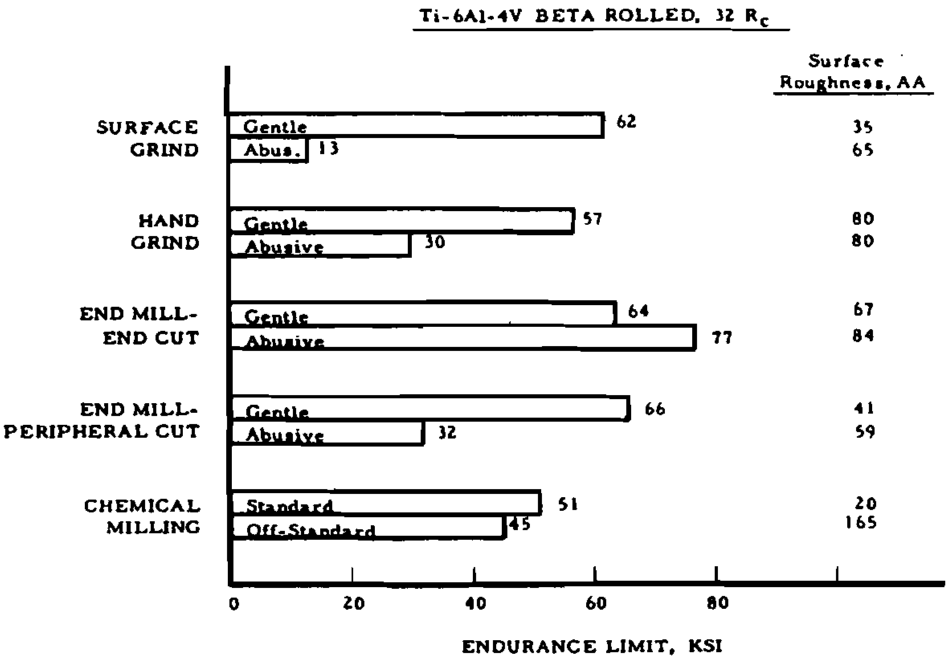


Figure 5. Endurance limit of gentle machining operations vs abusive machining operations (after Zlatin and Field [24]).

CUTTING FORCES AND STRESSES

Traditionally the forces in practical machining operations have been established by empirical approaches whereby the effects of the more obvious process variables such as feed, depth of cut, and cutting speed have been related to the experimentally measured average force components by means of curve fitted (or empirical) equations [40]. In comparison, the mechanistic modeling methods view the machining process as a combination of the chip load-cutting force relationship, cutting tool geometry, cutting process geometry, workpiece geometry, machining conditions, tool-workpiece displacement due to cutting forces and displacement feedback which changes the cutting conditions and effective tool geometry. In addition, the mechanistic models consider the effects of process noise factors such as runout, tool wear, and inhomogeneity of the workpiece material on the process responses such as cutting forces and surface accuracy [71]. It is obvious that the mechanistic model is more complex than the traditional empirical approach. Numerous researchers have attempted to apply mechanistic models to various machining operations. An application of this method to milling titanium alloys is studied by Yucesan and Altintas [41]. Their mechanistic model of end milling includes the influences of instantaneous chip thickness and rake angles. They conclude that at small radial immersions a decrease in the feed rate does not necessarily reduce the cutting forces since the cutting force factors increase exponentially at small chip thickness zones. The increase of the rake angle results in the decrease of the pressure at tool-chip interface and the increase of the friction coefficient. Consequently, for rake angles larger than 12°, no significant change in the cutting forces is observed (with the change of the rake angle) when machining titanium. They claim that their simulated cutting forces are in good agreement with the measured values.

The difficulty of applying the mechanistic model is the experiment calibration of force component coefficients for each cutter design, on which the predictive capability of the model rely. The amount of experiment could be prohibitive. In order to overcome this problem, Budak et al. [40] try to extend orthogonal cutting data to predict cutting forces in variety of oblique machining operations. They develop a unified mechanics of cutting to predict the milling force coefficients for use in the mechanistic approach. In addition to basic cutting quantities such as the shear stress, shear angle, and friction angle at the rake face from a set of orthogonal cutting tests at various cutting conditions and rake angles, the modified thin shear zone (or plane) analysis of classical oblique cutting incorporating the "edges" forces are also included. Experiments show that the accuracy of the predicted forces in the x and y direction are very good but the force in the z direction is poor.

Because the material removal process is so complex that it is difficult to understand completely the physical mechanisms involved. One way to circumvent this problem is to treat the process as a black box and somehow relate the input conditions and output qualities. A neural network is such a tool. Sathyanarayanan et al. [42] use a neural network to relate feed rate, depth of cut, and wheel bond type to surface finish, force, and power in creep feed grinding of superalloys including Ti-6Al-4V. An optimization model is based on the results of the neural network to minimize power, surface finish, and force. There are always considerable risks when we treat the process as a black box, especially when the system is nonlinear as it is in machining.

CHIPS OF MACHINING TITANIUM AND ITS ALLOYS

There are three principal chip types in machining [20]:

1. continuous chip;
2. continuous chip with built-up edge;
3. discontinuous chip.

Chips of machining titanium and its alloys under almost all practical cutting conditions belong to the third category. Their distinctive features are that they are serrated, shear-localized, discontinuous, cyclic, and segmented [2,25,43,44,45, 46,47,48]. Other materials including hardened steel show this type of chip only under certain machining conditions. Figure 6 shows a microstructure of Ti-6Al-4V without being cut and Figure 7 shows a typical Ti-6Al-4V catastrophically shear-failed chip. The strain in the chip is confined to narrow bands between the

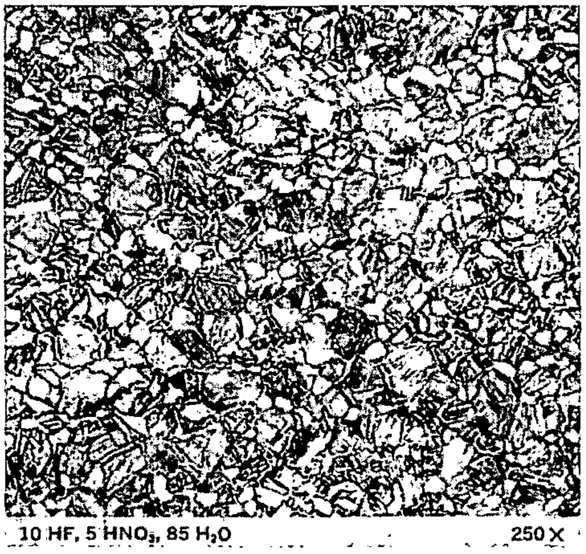


Figure 6. Microstructure of Ti-6Al-4V (after ASM Committee [15]).

segments with very little deformation within these segments [2,43,45]. The intensive shear takes place in a narrow zone rather than in a plane as is assumed by some investigations in the analysis of orthogonal machining process [43]. The chips have been classified as "catastrophic shear chips" and the forming process of which has been referred to as "catastrophic thermoplastic shear" or "adiabatic shear" [2,25,26]. The adiabatic shear bands have been classified into "deformed" and "transformed" types. Titanium and its alloys are capable of forming transformed shear zones undergoing martensitic phase transformation [26]. According

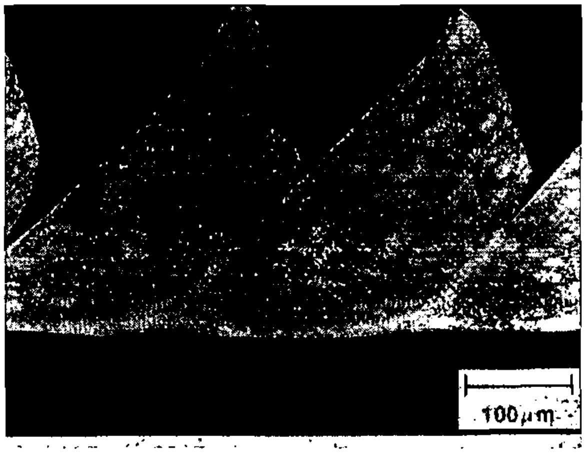


Figure 7. A typical Ti-6Al-4V catastrophically shear-failed chip (after Komanduri et al. [45]).

to Komanduri et al. [45], the serrated chip is practically independent of the response of the tool structure and there are two stages in the chip forming process. One stage involves plastic instability and strain localization in a narrow band in the primary zone ahead of the tool. The other stage involves upsetting the inclined wedge of work material by the advancing tool, with negligible deformation, forming a chip segment. They conclude that the conventional ''secondary shear'' between the chip and the rake face in Merchant's model is *not* pertinent to the case of the shear-localized chip formation process. (Note, however, the ''secondary shear'' has also been reported which conflicts this conclusion [2,25]). Colwell and Truckenmiller [28] are among early researchers who notice that Merchant's theory for continuous chip formation [72] is unable to capture the process of discontinuous chip formation in machining titanium alloys accurately. Later, Komanduri [49] claims that it is somewhat misleading to represent the chip formation process of machining titanium alloys by the conventional continuous chip formation model (such as that of Merchant [72]). One example is that the Merchant model leads many researchers to believe falsely that the shear angle is high when machining titanium alloys.

There are several factors that influence the formation of chips. First, microstructure. Motonishi et al. [30] suggest that the condition of segmentation vary according to the microstructure and that no conspicuous serrated chip is observed in α alloys. They also state that a typical serrated chip is observed in the α-β alloys and the adiabatic shear deformation occurs twice to form one chip serration in β alloys. Shahan and Taheri [26] also report similar findings on adiabatic shear band formation. Second, temperature. Dillon et al. [50] report that the smallest chips produced come from the machining of titanium at a workpiece temperature of $-190°C$, which is considered the most desirable for fully automatic machining. The reason could be due to the crack nucleation at twin intersections.

The shear localization has multiple effects [2,25,43,44,49]. First, such chips cause cyclic variation of force (both cutting and thrust) and consequent vibration or chatter in the metal cutting process and this in turn can encourage chatter to occur under unfavorable conditions, resulting an undulating surface finish. Second, with poor thermal properties, shear localization causes an increasing of the local temperature at the shear band to such a high value that it induces a phase transformation. Some non-diffusional phase transformation has been observed owing to the change in β structure into α phase during chip formation. Third, this high temperature can cause rapid chemical reaction and is most certainly responsible for the high tool wear on the rake face. Fourth, cavities have been observed in the shear band, which have a significant effect on the mechanical properties. Fifth, shear bands are good sites for fracture and nucleation of cracks since they are usually very brittle and have different microstructures with respect to matrix materials.

Shear instability is responsible for forming the serrated cyclic chips [25]. There are several existing criteria for shear instability, the mechanisms of which are summarized in Table 9. In a recent paper, Shaw and Vyas [66] claim that the

Table 9. Summary of Shear Instability Mechanisms

Thermo-plastic instability (Hou and Komanduri [25], Recht [64])	Strain hardening effect cancels thermal softening effect
Microcracks in the shear band (Komanduri and Brown [62], Shaw and Vyas [66], Shaw and Walker [67]).	Microcracks lead to a reduction in the actual area undergoing stress. Used to explain low-cutting speed cyclic chips and larger shear case.
Structural transformation (Lemire and Backofen [63]).	As in the reversion of martensite to austenite.

root cause of high frequency, saw toothed chip formation is found to be periodic gross shear fracture extending from the free surface of the chip toward the tool tip and not adiabatic shear as commonly believed. Many researchers believe that there exists a critical value when the continuous chip becomes the serrated, shear-localized chip and have attempted to determine it. Table 10 is a summary of these values. The cutting speed is the most influential variable, which has been explained on a purely thermally activated process that may not be reliable: when the cutting speed decrease to the "critical value," the deformation becomes uniform and the distance between the shear bands approaches zero because thermal gradients become negligible [2].

Obikawa and Usui [47] develop a finite element model for analyzing discontinuous or shear-localized chips. The two-dimensional elastic plastic analysis was formulated in updated Lagrangian form for large deformation problems in metal cutting. Unsteady state heat conduction, material nonlinearities, friction on the rake face, crack and computational flow stress characteristic of the titanium alloy at high strain rate and high temperature are considered. The computational results

Table 10. Summary of Critical Value for Onset of Shear-localized Chip

Recht [64]	Zero slope on true stress-true strain curve
Hou and Komanduri [25]	Cutting speed V corresponding to $\sigma' < \sigma$, where σ' is the shear stress calculated in the shear band and σ is the shear strength at the preheating temperature. V = 9 m/min for Ti-6Al-4V V = 130 m/min for ANSI 4340 steel
Bayoumi and Xie [43]	Chip load Vf, where V is the cutting speed and f is the feedrate. Vf varies for different tool-workpiece material combinations. With cemented-carbide cutting tips, Vf = 0.004 for Ti-6Al-4V Vf = 0.006 for AISI 4340 steel
Semiatin and Rao [65]	(normalize flow softening rate)/(strain rate sensitivity) ≥ 5
von Turkovich and Durham [48]	When the strain and the strain rate imposed in the deformation zone are larger than those corresponding to the locus $\partial\tau/\partial\gamma = 0$

of the shape and somewhat irregular pitch of the serrated chips resemble those observed in actual metal cutting tests.

HEAT TRANSFER AND CUTTING TEMPERATURE

In metal cutting, about 90% of the plastic work is converted into heat [26,43]. The heat partition between the cutting tool and workpiece depends on the thermal properties of both materials. As titanium and its alloys are notoriously poor heat conductors [23], usually a larger portion of heat generated in machining process will be absorbed by the tool. According to Konig [51], the percentage of heat absorbed by the tool is a function of tool materials used and can be as high as 80% when machining Ti-6Al-4V (Figure 8). In comparison, a maximum of between 50% and 60% heat generated can be absorbed when machining steel.

The poor thermal properties together with the high strain rate in machining give rise to adiabatic or quasi-adiabatic shear bands because the heat generated can not be dissipated [26,43]. Shahan and Taheri [26] consider the high dependence of flow stress on temperature and low strain-hardening rate as contributing factors as well. The analysis of the microstructure suggests that the maximum temperature rise during formation of the shear band occurs at the center of the zones. It has been reported that the temperature gradient are much steeper and the heat-affected zone smaller and much closer to the cutting edge, even at lower speed, than when iron is machined by Smart and Trent [52], and Freeman [53]. Freeman explains that the highest temperature is produced closest to the cutting edge of tool because

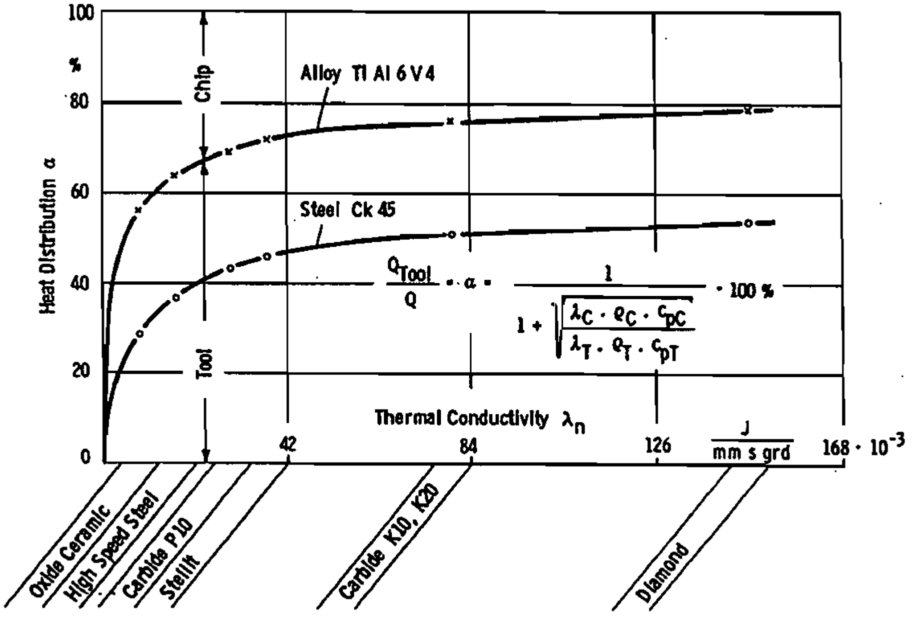


Figure 8. Distribution of thermal load on turning tools (after Konig [51]).

of the thin chips, a thin secondary shear zone and a short chip-tool contact length. The stronger the work material (the higher amount of β phase), the higher the temperature produced during machining at the same cutting conditions. However, Motonishi et al. [30] conclude that no definite relation is recognized with regard to the microstructure as far as cutting temperature is concerned.

Hou and Komanduri [25] identify the temperature rise in the shear band as due to the following three heat sources as well as the preheating effects of these sources based on an analysis of the cyclic chip formation. The three primary heat sources are the main shear band heat source that will be predominant heat source especially at higher cutting speeds, the secondary shear band heat source that is generated during the upsetting stage of cyclic formation, and the frictional heat source between the segment already formed and the rake face of the cutting tool. (It is interesting to note that Komanduri et al. [45] claim that the secondary shear band was not observed in machining.)

Tool flank wear is a major cause of thermal damage in the machined surface layer. A new methodology is developed to provide the knowledge needed for understanding the heat transfer regarding the formation of the thermal damage and the cutting mechanics in finish hard machining [74,75]. The methodology consists of a thermal model based on Green's function and a microstructure-based method using orthogonal hard turning. The thermal model describes the heat transfer of a worn tool with heat sources at the tool-chip interface due to chip formation and at the tool-work interface due to flank wear. The coupling of the interface boundary conditions due to chip formation and flank wear is resolved using the proposed microstructure-based method, which is a departure from the conventionally incorrect approaches based on the assumption of constant chip formation. By incorporating the microstructure-based method with the thermal model, heat generated, heat partition, and the shear forces at the tool-chip and tool-work interfaces can be determined. Interface temperatures that are extremely difficult to be measured are obtained. The results quantitatively explain how the heat transfer and chip formation are altered as the tool flank is progressively worn. This method can be used when there is a layer of microstructure change induced by wear.

TOOL WEAR

The high temperature generated in machining titanium which acts close to the cutting edge of the tool is the principal reason for the rapid wear of tools. Both the high temperature and the high stresses developed at the cutting edge of the tool may cause plastic deformation and/or accelerate the wear of the tools [51,55]. The serrated-chip formation is assumed to make great contribution to flank wear [30].

Tool life can be expressed as the time or volume of material removed before a cutting tool becomes worn out or fracture. During metal cutting, the tool develops a wearland and/or a crater. The wearland is most commonly used as a tool-life criterion [22]. In machining titanium alloys, small changes in cutting speed

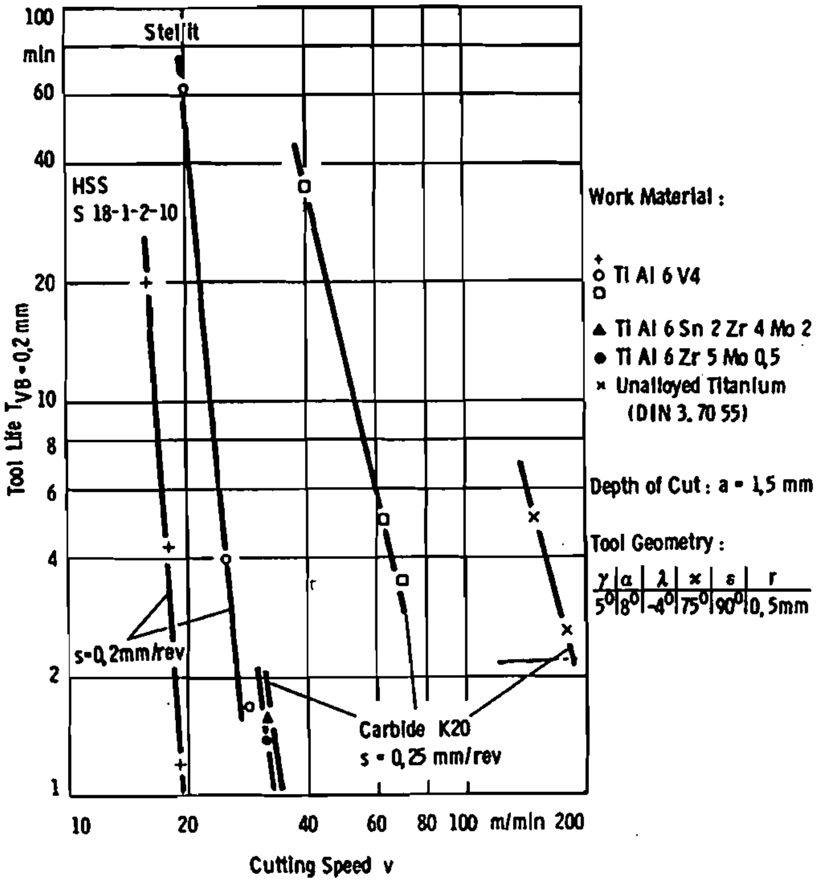


Figure 9. Turning-tool life and cutting conditions (after Konig [51]).

cause extremely high changes in tool life. To obtain maximum material removal rates the feed should be selected as high as possible (Figure 9, [51]). Often, tool life does not vary greatly with change in feed. Tool life in machining titanium alloys, however, is very sensitive to changes in feed (Figure 10, [22]).

Wear mechanisms in machining titanium alloys may vary according to different cutting tool/workpiece materials combination and include attrition, diffusion, and dissolution [1,53,55].

Basically, there are many ways to improve tool life for a given set of cutting variables. The first one is to change tool materials. The second one is to use a cutting fluid. The third one is to change the properties of workpiece materials during cutting or permanently. The second approach will be covered later in this section while the third approach will be covered in the section on Non-conventional Methods of Machining. The reason behind the first approach is that tool wear rate is a function of cutting tool materials (Table 11) because different tool materials tend to have different response to different wear mechanisms. Extensive research has been carried out to study the performance of different tool materials.

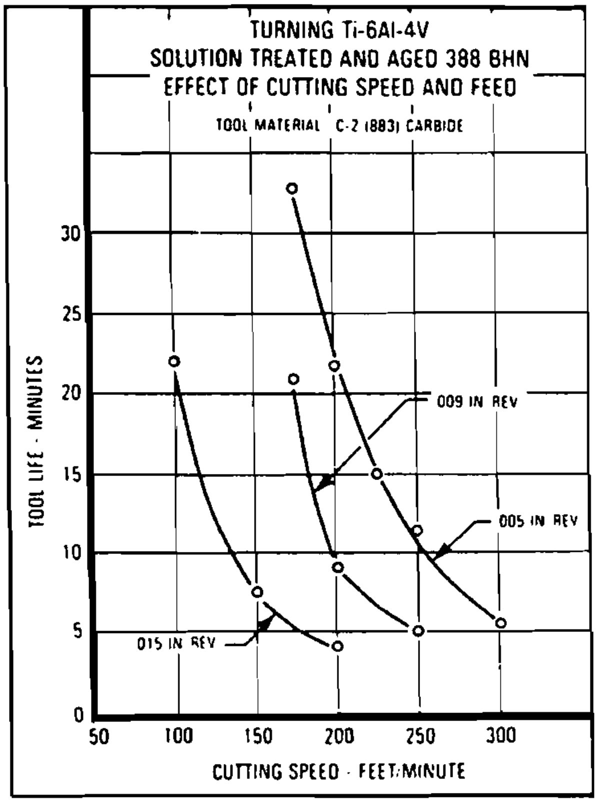


Figure 10. Effect of cutting speed and feed on tool life in turning Ti-6Al-4V (after Kahles et al. [22]).

Dearnley and Grearson [55] report that boron-based tool materials have significant potential for combating wear caused by dissolution-diffusion (Table 12). The success of CBN tool in machining titanium alloys has also been confirmed by Lee [57] who reports that CBN tools with good thermal conductivity can be used for an extended period in machining titanium alloys with cutting speed up to 700 ft/min. The chip material and cutting tool seizure problem was not observed in the case of high speed machining. Bhaumik et al. [1] conclude that a WBN-CBN composite tool can be used economically to machine titanium alloys. The success of the composite tool is due to its high fracture toughness coupled with high hardness and, especially, hot hardness. WC/Co alloys and natural diamond have been reported to perform well in machining titanium. The high cost of CBN and diamond tools limits their applications [2,55]. High-speed steel tools are best suited to interrupted cutting and drilling, reaming, and tapping. For continuous cutting and also for slab and face milling at high production rates, carbide tools are normally used [2,55]. Hartung and Kramer [56] suggest that tool wear is greatly reduced when adhesion occurs between the tool and the chip, preventing relative sliding at the tool/chip interface.

Table 11. Wear Rates for Various Tool Materials (after Dearnley and Grearson [55])

TOOL TYPE	CUTTING SPEED m/min	FEED RATE mm/rev	TEST TIME s	ATMOSPHERE*	MAXIMUM FLANK WEAR LAND mm	MAXIMUM CRATER DEPTH µm	MAXIMUM CRATER WEAR RATE µm/min	NOTCH DEPTH mm
Cemented carbide	75	0.25	30	A	0.04	12	24	0
(−5° rake)	75	0.25	30	N	0.04	10	20	0
White ceramic	75	0.25	30	A	0.40	230	460	1.45
	75	0.25	30	N	0.40	210	420	1.00
White ceramic	75	0.25	20	A	0.28	161	483	0.80
	75	0.25	20	N	0.40	150	450	0.92
$Al_2O_3 - 30ZrO_2$	35	0.16	30	A	0.12	65	130	0.40
	35	0.16	30	N	0.10	78	156	0.48
	75	0.25	5	A	0.20	150	1800	0.84
	75	0.25	5	N	0.20	136	1632	1.20
Mixed ceramic	75	0.25	5	A	0.20	165	1980	1.80
	75	0.25	5	N	0.20	192	2304	1.80
Sialon	35	0.16	30	A	0.04	32	64	0.08
	35	0.16	30	N	0.12	38	76	0.72
	75	0.25	30	A	0.20	350	700	1.20
	75	0.25	30	N	0.20	57	114	0.80
Sialon with ex-	75	0.25	30	A	0.20	58	116	0.80
tended chamfer	75	0.25	30	N	0.24	44	88	0.88

*A, cutting in air; N, cutting in a jet of nitrogen.

Table 12. Wear Data for Cubic Boron Nitride Used to Cut Ti-6Al-4V for 30 s at 0.25 mm/rev and 1.5 mm Depth of Cut (after Dearnley and Grearson [55])

CUTTING SPEED m/min	MAX. FLANK WEAR LAND, mm	MAX. CRATER DEPTH, μm	MAX. CRATER WEAR RATE μm/min
45	0.04	35	70
100	0.04	35	70
200 (test 1)	0.20	55	110
200 (test 2)	0.16	50	100
250	0.60	106	212

The cutting tool geometry has an impact on the tool life. Komanduri and Reed [13] propose a new cutting geometry consisting of a high clearance angle together with high negative rake angle to increase cemented tungsten carbide tool life.

Zlatin and Field [24] have given some suggestions on selecting appropriate cutting conditions to increase the tool life.

Because the thermal properties of titanium and of its alloys are so poor, the application of cutting fluids are extremely important. Different types of cutting fluids have different performances. The cutting fluids containing phosphates give the best results [2]. Chlorine is considered a suspect element because it could cause stress-corrosion cracking [22]. Campbell [7] compares two coolants in grinding and concludes that straight oil fluid is one of the major factors that produces the maximum compressive residual stress and water-soluble fluid makes higher metal removal rates possible. Several researchers have studied the high-pressure coolant [31,46,54]. In addition to cooling, another function of the high pressure coolant is that it breaks the chip. Other findings include that the high pressure cooling system reduces the chip-tool contact length, causes no significant changes in the cutting forces, and does not cause any significant alteration in the surface condition of the machined surface. Please refer to the next section for more information.

NON-CONVENTIONAL METHODS OF MACHINING

Machado and Wallbank [2] summarize some non-conventional methods of machining titanium and its alloys. The General Electric Company has developed tools with special geometry (ledge tools) or special configuration (rotary tools) that have longer tool life than conventional tools. The ledge tools have special geometry that limits the maximum flank wear of the tool. The life of the tool is limited only by the ledge size. However, they can only do straight cuts. Another limitation is the depth of cut which must be equal to or less than the width of the ledge overhang. The rotary tools make the lubrication and cooling easier. The temperature can be distributed more broadly. Life improvements of some 7 times over a conventional tool have been reported. However, the inserts of rotary tools must be circular, which minimizes their effectiveness for machining complex surfaces and may limit the depth of cut. Ultrasonically assisted metal removal (UAMR) have improved surface finish, reduced sub-surface deformation, altered chip characteristics by encouraging chip fracture, eliminated the built-up edge, and extended tool life. Large improvements have been observed mainly in drilling free machining titanium. It is a method by which certain properties of titanium alloys have been modified by adding both sulphur and rare earth additions. The result of this is to encourage chip segmentation and apparently reduce the cutting temperature. Tool life in both drilling and turning has been improved substantially while chip formation has also shown some improvement.

The effect of high-pressure coolant jet on machining of titanium and its alloys has been reported by some papers. The pressure of the jet is 45 ksi [31] and 14.5 Mpa [46]. They [31,46] both conclude that the high-pressure coolant jet is an efficient chip-breaker. The tool lives in machining Ti-6Al-4V have been extended significantly [46] or by 2 to 20 times [31] compared to conventional lubri-coolant techniques because HP cooling system retards the major wear mechanism (diffusion) [46]. However, the HP cooling system generally reduce tool lives when machining the nickel alloy [46]. Kumagai et al. [54] report that increased jet pressure of grinding fluid decreases surface roughness and depth of grinding layer, and increase surface hardness.

The titanium alloys properties can be modified before machining operations to improve machinability. After the machining operations, the original properties of the materials can be recovered. Kolachev and Egorova [58] report that hydrogen alloying of titanium alloys results in cutting area temperature decrease by 50-150°C, significant reduction of cutting forces and increase of tool life in 2–10 times. The favorable influence of hydrogen on machinability of titanium alloys by cutting is due to refinement of metal structure during hydrogenation, reduction of flow stresses of the metal being machined and its toughness, increase of thermal conductivity of titanium, and change of character of the tool wear. The hydrogen can be easily removed from titanium alloys by vacuum annealing, which not only recovers the original metal properties but improves them at the definite conditions of thermohydrogen treatment. The cost-effectiveness of this method is unknown.

Electro-discharge machining (EDM) is one of the non-traditional machining methods widely used on electrically conducting materials. The electrode of an EDM machine can be either rotating or stationary. Soni and Chakraverti [39] report that rotary mode of EDM is better than stationary mode in machining titanium. Surface roughness, over-cut, and out-of-roundness increase with increasing current with both rotating and stationary electrodes.

Cryogenic machining of titanium alloys shows a potential to lend itself to fully automatic machining [50].

SUGGESTED FUTURE RESEARCH

Titanium and its alloys are difficult-to-cut materials. Their fabrication cost is high, and so is the materials cost. In order to reduce these costs, more research is needed. Based on the literature review, it is proposed that the following can be good research directions.

Machinability

The machinability of titanium and its alloys needs to be improved. There are three ways to improve the machinability that deserve study, with the goal for reducing the production cost of using titanium alloys. First, the application of CBN and Diamond tools. Although the CBN and Diamond tools are not new and show good potential to increase machinability of titanium and its alloys, their applications have been limited by their high cost. This problem could be overcome by making machining a finishing process thus eliminate other finishing processes such as grinding. The significance of eliminating grinding process also lies in that the surface of titanium alloys is easily damaged during grinding. The feasibility of using machining as a superfinishing process on hardened steel has been demonstrated by Liu and Mittal [60,61]. Surface roughness of up to 2 μin has been achieved. Similar research needs to be done on machining titanium alloys. Second, designing better cooling systems so that the high temperature in machining titanium alloys can be relieved, which could lead to longer tool life, higher cutting speed, and better surface integrity. The high pressure coolant system shows a good potential, however, it could also reduce tool life and no explanations are given as of why this happens [46]. No model has been seen to relate the pressure of the coolant and the way the coolant is applied (the location and the angle of the high pressure coolant) and the effectiveness of the cooling system. This model is needed in order to optimize the cooling system. Third, changing the material cutting characteristics without reducing the strength (dynamic as well as static) of the material. Free machining titanium is one example. An interesting way is to change the material structure temporarily during the machining process [58]. This could be a promising way if the cost is justified. The cost-effectiveness of this method needs to be studied.

Process Model and Performance Model and Their Linkage

As titanium alloys are used as important structural materials that are often subjected to cyclic loading, the fatigue strength of machined components is extremely important. However, this knowledge is at best collected experimental data. Quantitative knowledge is still lacking. One way to overcome this problem is to establish process models and performance models that have predictive power. By linking these two models, the cutting parameters can be optimized to gain the best surface integrity for optimized fatigue life. Figure 11 (after Mittal and Liu [59]) shows the flow chart for manufacturing roller bearings that can be adapted to achieve this goal in machining titanium alloys. The potential to save significant material by this approach is promising, which could solve the high material cost associated with the using of titanium alloys.

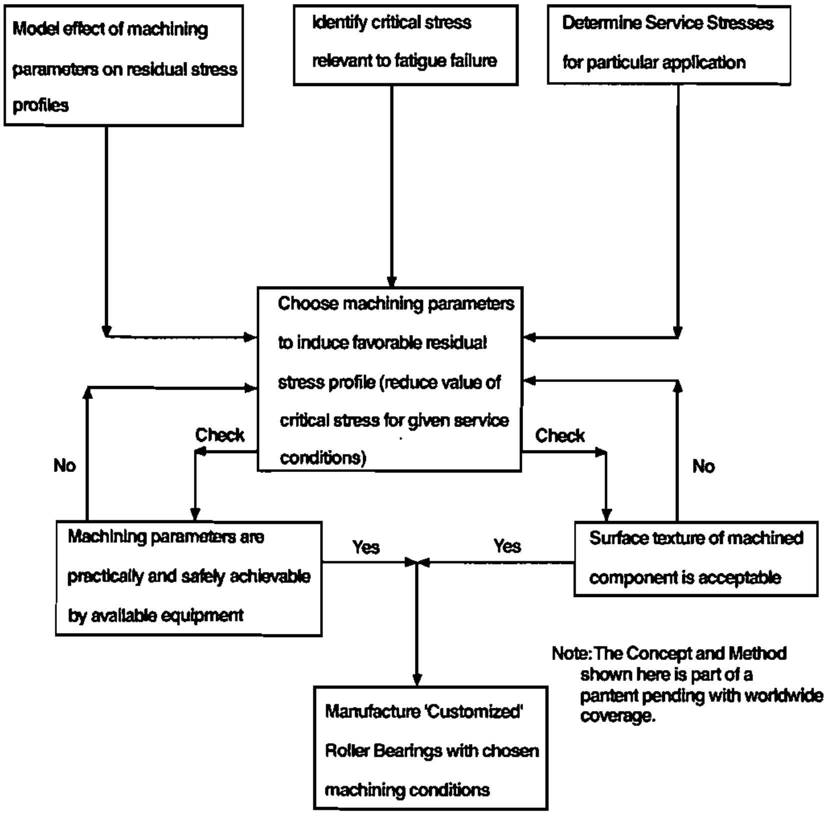


Figure 11. Flowchart for manufacturing customized roller bearings (after Mittal and Liu [59]).

Modeling Heat Transfer and Thermal Damage

Since the temperature gradient in the machined surface is extremely large, and thermal damaged layer is typically very thin, an accurate thermal modeling approach is needed. Theoretically the thermal behavior can be studied by finite element. However, the method of building accurate material models under the strain rate of metal cutting are still not available. A parallel and readily available method based on the thermal damage observed in the chip [73,74,75] can be adapted to study the heat transfer and thermal damage behavior in machining titanium.

Finite Element Modeling

Very limited work has been done on finite element simulation of machining titanium alloys. This is an area deserving more study because the machining process is so complex that a close form analytical model is unlikely to be established. A good finite element model would be very useful to optimize the machining process so as to reduce its cost and improve the quality. Material property models to describe the material behavior under high temperature, high strain, and high strain-rate and tool-chip friction accurately are still lacking. These models need to be established first.

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