MECHANICAL DRILLING PROCESSES FOR TITANIUM ALLOYS: A LITERATURE REVIEW

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Abstract

Titanium and its alloys (Ti) are attractive for many applications due to their superior properties. However, they are regarded as hard-to-machine materials. Drilling is an important machining process since it is involved in nearly all Ti applications. It is desirable to develop cost-effective drilling processes for Ti and/or improve the cost-effectiveness of currently-available processes. Such development and improvement will be benefited by a comprehensive literature review of drilling processes for Ti. This paper presents a literature review on mechanical drilling processes for Ti, namely, twist drilling, vibration assisted twist drilling, ultrasonic machining, and rotary ultrasonic machining. It discusses cutting force, cutting temperature, tool wear and tool life, hole quality (diameter and cylindricity, surface roughness, and burr), and chip type when drilling of Ti using these processes.

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1. Introduction

The primary application of titanium and its alloys (Ti) is in the aerospace industry. Usage of Ti is widespread in most aircraft, as well as in spacecraft. For example, Ti is used in the primary structure of the F-22 fighter (Boeing, 1996). On the Boeing 787, use of Ti has been expanded to roughly 14 percent of the total airframe (Hale, 2006). Ti is also used for many parts in gas turbine engines (such as blades, discs, and rotors) and for many non-structural applications in aircraft (such as floor support structure, tubes or pipes, clips and brackets) (Peacick, 1988; Boyer, 1995).

Ti is also widely used in such industries as automobile (Anonymous, 1989; Yamashita et al., 2002), chemical (Farthing, 1979; Orr, 1982; Salama et al., 2000; Schutz et al., 2001), medical (Abdullin et al., 1988; Froes, 2002), metallurgic (Anonymous, 2004; Orr, 1982), military (Montgomery and Wells, 2001; Lerner, 2004), and sporting goods (Froes, 2002). The rapid advance of the application of Ti in the past several decades has been matched by a dramatic growth of the Ti industry. It was estimated that the worldwide demand for Ti would be over 136,000 tons (or, 300 million pounds) by 2015 (Haflich, 2006).

The primary source for the increasing popularity of Ti is its superior properties such as high strength/weight ratio, high compressive and tensile strength, low density, high fatigue resistance in air and seawater, and exceptional corrosion resistance (Farthing, 1979; Kumar, 1991; Schutz et al., 2001; Trucks, 1987; Yamashita et al., 2002; Yang and Liu, 1999). Other reasons include its availability in the earth's surface and price stability (Farthing, 1979; Orr 1982). The detailed information about the properties of Ti are readily available in the literature (Farthing, 1979; Trucks, 1987; Rao et al., 1990; Yang and Liu, 1999).

However, Ti has been classified as difficult-to-machine material. Seven reasons were listed by Yang and Liu (1999). Among these reasons, the first is its poor thermal conductivity. Since the workpiece will not help getting out the heat generated in machining, the heat tends to concentrate at the cutting edge, causing the edge temperature to easily reach 1000ºC (Thorne, 2001). This will result in short tool life. The second reason is its strong affinity to many tool materials (especially at high temperatures) (Dornfeld et al., 1999; Kumar, 1991). This will also cause rapid tool wear. Furthermore, because Ti can retain its hardness and strength at high temperatures, the force and stress on the cutting edge will be higher (Thorne, 2001). This can potentially cause some tools to fail. Therefore, Ti machining usually encounters the problems of high tool wear rate, high machining cost, and low productivity. There is a crucial need for cost-effective machining processes applicable to Ti.

Among all Ti machining methods, drilling (or hole making) is very important. It accounts for a large percentage of all machining processes and is essential for many applications (Schroeder, 1998; Tonshoff et al., 1994). It is usually one of the final steps in the fabrication of mechanical components and has considerable economical importance (Li and Shi, 2007).

Several review papers related to Ti machining have been published. Yang and Liu (1999) provided a comprehensive review on machining of Ti. They started with metallurgy and machinability of Ti, and covered turning, milling, grinding, and nontraditional processes (such as ultrasonic assisted machining, electro-discharge machining, and cryogenic machining). Their focus was not on drilling and they reviewed the literature up to 1998. Singh and Khamba (2006) gave a review of ultrasonic machining (USM) of Ti. They described the construction of the ultrasonic machine tool and the material removal mechanisms of USM. Rahman et al. (2006) reviewed high-speed machining (HSM) of Ti. They summarized the HSM of Ti with different tools and discussed the modeling and simulation of HSM of Ti. Yeo et al. (1994) provided a technical review on laser drilling of Ti. They discussed the characteristics, parameter effects, and modeling in laser drilling of Ti.

This paper will be the first review paper providing a comprehensive review on mechanical drilling processes for Ti. It covers twist drilling, vibration assisted twist drilling, ultrasonic machining (USM), and rotary ultrasonic machining (RUM). It concentrates on several essential aspects, namely, cutting force, cutting temperature, tool wear and tool life, hole quality (diameter and cylindricity, surface roughness, and burr), and chip type.

2. Important aspects in titanium drilling

2.1 Cutting force

Cutting force can be an indication of how difficult a material is machined (Colligan, 1994; Kim et al., 2005; Lambert, 1979a). Usually, a smaller cutting force is desired. An increase in the cutting force can cause the spindle axis to vibrate, causing poor quality of machined surfaces. It can also cause premature failure of drills and reduce the drill life. Large torque, which often indicates more friction between the drills and workpiece, can produce a large quantity of heat, causing higher temperature at the tool-workpiece interface.

It was reported that the cutting force when drilling Ti was higher than that when drilling aluminum alloys (Yang and Liu, 1999), similar to that when drilling steels (Ezugwu, 1997). The power consumption when drilling Ti was approximately the same as or lower than that when drilling low hardness steels (Kahles et al., 1985). Fig. 1 and Fig. 2 compare, respectively, the cutting force and power consumption when drilling different metals.

Although the cutting force when machining Ti is not much higher than that when machining other metals, much higher stresses occur in the immediate vicinity of the cutting edge when machining Ti. Konig (1979) reported higher stresses on the tool when machining Ti-6Al-4V than those when machining a nickel-based alloy, and three to four times higher than those when machining steel. He attributed this to the unusually small chip-tool contact area on the rake face (about one-third of that when machining steel for the same feedrate and depth of cut), and partly to the resistance of Ti to deformation at elevated temperatures.

2.2 Cutting temperature

During drilling process, about 90% of the work of plastic deformation is converted into heat, producing very high temperatures in the deformation zones and the surrounding regions of the interfaces between the chip, tool and workpiece (Bayoumi and Xie, 1995; Ezugwu, 1997; Li, 2007; Shahan and Taheri, 1993). The heat partition between the cutting tool and workpiece depends on the thermal properties of both materials. Because of Ti's poor heat conductivity (which is about 1/6 of that for steels) (Anonymous, 1993), a larger portion (as high as 80%) of heat generated in Ti drilling will be absorbed by the tool (Konig, 1979; Li, 2007). In comparison, 50% to 60% of the heat generated when drilling steel is absorbed by the tool (Child and Dalton, 1965). High cutting temperature is an important reason for the rapid tool wear commonly observed when drilling Ti (Ezugwu, 1997).

2.3 Tool wear and tool life

Ti chips can easily weld to the cutting edges of the tool (a.k.a., built-up-edge, or, BUE). It is particularly so once tool wear begins (Barish, 1988; Trucks, 1981). BUE usually leads to chipping and premature failure of the tool. When machining Ti, the tool wear progresses rapidly because of high cutting temperature and strong adhesion between the tool and workpiece (Narutaki and Murakoshi, 1983). And the high stresses developed at the cutting edge of the tool may cause plastic deformation and/or accelerate the tool wear (Dearnley and Grearson, 1986; Dornfeld et al., 1999; Ezugwu, 1997; Konig, 1979; Sharif and Rahim, 2007; Yang and Liu, 1999).

Wear mechanisms in machining Ti may vary according to different tool/workpiece material combinations. Notching, non-uniform flank wear, crater wear, chipping, and catastrophic failure are the prominent failure modes when drilling Ti (Ezugwu, 1997; Rahim and Sharif, 2006; Sharif and Rahim, 2007).

Severe tool wear is the main reason for the high cost of Ti drilling. The cutting speed must be sufficiently low to avoid too short tool life. In order to ensure the tool life, it usually takes a longer time to drill Ti than steel (Yang and Liu, 1999). Fig. 3 shows relative time consumption when drilling different metals.

2.4 Hole quality

Hole quality in drilling Ti is evaluated in terms of hole diameter and cylindricity, surface roughness, and burr (Kim et al., 2001). Ti is generally used for parts requiring the great reliability and resistance of wear, and therefore high hole quality must be maintained. Higher surface roughness can possibly lead to severe wear, catastrophic fatigue, and lower ability to resist corrosion. However, the surface of Ti is easily damaged during machining operations (Child and Dalton, 1965; Konig and Schroder, 1975). Damage appears in the form of microcracks, plastic deformation, heat-affected zones, and tensile residual stresses (Kahles et al., 1985; Koster, 1973; Narutaki and Murakoshi, 1983).

Two critical criteria (hole diameter and cylindricity) were usually applied to determine the hole quality in terms of size and shape. The average hole diameter has to be within the size tolerance which is described as two concentric circles. Cylindricity is the extension of roundness into the entire length of the hole. The cylindricity tolerance zone is established by two concentric cylinders between which the machined hole (a cylinder) must lie (Anonymous, 2007; Kim et al., 2001).

Most Ti drilling processes will create a burr on both entrance and exit surfaces. In most cases the main concern is the exit burr which is much larger in size. Burr formation in Ti drilling is troublesome in aerospace applications. It is estimated that up to 30% of the cost of some components is due to deburring operations (Dornfeld et al., 1999).

2.5 Chip type

In twist drilling and vibration assisted twist drilling, the Ti chip could be entangled around two flutes of the drill and bent by the tool holder. This chip entanglement will cause difficulty for smooth chip ejection (Li et al., 2007).

The characteristic of the chip formation in twist drilling of Ti is different from other metals (Kim and Ramulu, 2005a; Yang and Liu, 1999). Yang and Liu (1999) categorized the Ti chips into three types: continuous chip, continuous chip with built-up edge, and discontinuous chip. The distinctive features of Ti chip can be described as serrated, shear-localized, discontinuous, cyclic, and segmented (Bayoumi and Xie, 1995; Hou and Komanduri, 1995; Machado 1990). There are two main shapes of chip morphology: spiral cone chip and folded long ribbon chip. It has reported that the spiral cone chip is easier to be ejected so the length of spiral cone chip can be considered as a scale to evaluate the difficulty for chip evacuation in drilling.

Generally, Ti chips are thin and the flow zone between the chip and the tool is also much thinner (approximately 8 μm compared with 50 μm when cutting iron under the same cutting conditions) than some other metals, so the tool-tip temperatures can be up to about 1100ºC (Motonishi et al., 1987; Narutaki and Murakoshi, 1983). Besides, the adhesion often occurs easily to the tip of the drill when drilling Ti and it will lead to the increase in the cutting resistance and chip jamming within the flutes of drill (Okamura 2006). As a result, it leads to the drill breakage and the decrease of the hole accuracy (Cantero et al., 2005, Wang et al., 2005).

3. Twist drilling

3.1 Description and features of twist drilling

Twist drilling (as illustrated in Fig. 4) is the most common hole making method. Important process parameters in twist drilling include feedrate, cutting speed, drill geometry and material, and coolant.

The important geometric parameters for a typical twist drill are: rake angle, helix angle, side cutting edge, point angle, lip relief angle, and chisel edge angle (Barish, 1988; Dornfeld et al., 1999; Rao et al., 1990; Zhu and Wang, 2006). Twist drills are made in a wide variety of types with different materials, shapes, dimensions, and tolerances. The diameters of twist drills range from 0.05 mm to 100 mm, and the length can be up to 1000 mm (Anonymous, 2008). A merit of twist drilling process is the low cost and large quantity of drill supply. Several commonly used drill materials for Ti drilling are high-speed-steel (HSS), WC-Co carbide, HSS-Co carbide, CBN, WBN-CBN composite, and TiAlN-PVD coated tools (Kim et al., 2001; Li, 2007; Li et al., 2007).

However, twist drilling is usually not considered to be a precision process. The twist drills with basic designs are generally limited to hole depths of about three to five times the hole diameter (Drozda and Wick, 1983). Special requirements such as extremely small size hole and high precision dimension usually call for some other drilling methods. As for Ti, twist drilling is partially adequate especially with some innovation on the drill for particular drilling conditions (Barish, 1988; Colligan, 1994).

3.2 Cutting force in twist drilling

Effects of feedrate

The most significant parameter of a drilling process affecting the cutting force is feedrate. It has been consistently reported that an increase in feedrate would increase the thrust force (Kim and Ramulu, 2005a, d; Kim et al., 2005; Lambert, 1979a; Ramulu et al., 2001; Rao et al., 1990) and the torque (Kim et al, 2005; Lambert, 1979a; Rao et al., 1990), as shown in Fig. 5 (a) and (b).

Effects of cutting speed

It was reported that an increase in cutting speed would reduce the thrust force and torque when drilling Ti (Kim et al, 2005; Kim and Ramulu, 2005b; Lambert, 1979a; Li, 2007; Li et al., 2007; Rahim and Sharif, 2006), as illustrated in Fig. 5 (c) and (d). However, Kim and Ramulu (2005a) reported that the increased speed could reduce the thrust force but increase the torque when drilling Ti/composite stacks.

Effects of drill geometry and material

Both drill geometry and material have significant effects on the cutting force in Ti drilling. When the side cutting edge angle increased, the cutting force and torque would increase (Zhu and Wang, 2006). A larger helix angle would reduce both thrust force and torque (Rao et al., 1990). Rake angle was found to have little impact on the cutting force (Zhu and Wang, 2006). The exact effects of other geometric parameters are not available in the literature.

Li et al. (2007) reported that WC-Co drills performed better than HSS tools because of lower thrust force and torque. The WC-Co spiral drills (a kind of twist drill with advanced geometric design with S-shaped chisel edge and lower negative rake angle than that of the conventional twist drill) produced lower cutting force and torque than WC-Co twist drill, as shown in Fig. 6. Kim et al. (2001) reported that, when drilling Ti/graphite stacks, the torque with HSS-Co tools was at least 40% higher than that with carbide tools.

Effects of coolant

Li et al. (2007) reported that the external coolant supply had no obvious effect on the thrust force and torque, but internal coolant supply could slightly increase the thrust force (likely caused by the hydrodynamic force) and the consumed energy during the drilling process.

Effects of other factors

Kim and Ramulu (2005a) reported that typical thrust force and torque profiles varied with cutting depth as the drill penetrated the composite material when drilling Ti/composite stacks. Thrust force increased proportionally to an optimal depth then it dropped to a lower level for higher depth of cut. The thrust force was the maximum as the drill penetrated Ti and the maximum torque occurred when the drill lips cut both composite and Ti simultaneously.

Lambert (1979a) reported that the drilling force could be influenced significantly by the drilling time. Increased drilling time resulted in increased thrust force.

3.3 Cutting temperature in twist drilling

Rahim and Sharif (2006) reported that, as the cutting speed increased, so did the average temperature, while the range of temperature oscillation (or the difference between the maximum and minimum temperature values) decreased. At lower speeds, the magnitudes of temperature oscillations were 30% of the maximum temperature. As the cutting speed increased, the frequency of temperature oscillation increased (Brown and Hinds, 1985).

3.4 Tool wear in twist drilling

Effects of feedrate

Tool wear in Ti drilling is very sensitive to change in feedrate (Aust and Niemann, 1999; Ezudwu, 1997; Yang and Liu, 1999). As feedrate increased, tool wear increased and drill life declined (Li et al., 2007).

Effects of cutting speed

Cutting speed was shown to have a significant effect on the drill wear. A small change in cutting speed could cause a very large change in tool wear rate (Ezudwu, 1997; Yang and Liu, 1999). It was reported that tool wear was extremely severe at high cutting speeds but improved dramatically as the speed decreased (Ezudwu, 1997; Rahim and Sharif, 2006; Sharif and Rahim, 2007).

Effects of drill geometry and material

An increase in drill diameter could cause negative effects on the tool life (Aust and Niemann, 1999). A larger helix angle was shown to be better for the tool life since larger helix angle could reduce the thrust force and torque, but too large a helix angle could lead to the restriction of the chip egress (Barish, 1988; Rao et al., 1990). Barish (1988) provided a list of optimal drill geometry (such as drill point angle, chisel angle, lip relief angle, splitting angle, and the angle of notch) for drilling Ti. Zhu and Wang (2006) listed the order of these factors affecting tool wear (from greater to smaller) as: relief angle, rake angle, eccentricity of drill point, and side cutting edge angle.

Zhu and Wang (2006) reported that a drill material with higher hardness and higher density was more wear-resistant. For example, carbide tools might be required instead of HSS tools to improve the tool life when the hardness level of Ti was above 38 Rockwell (Trucks, 1987). Yang and Liu (1999) listed some potential cutting tool materials (which could be used to improve the tool life during Ti drilling) such as boron-based tool material, CBN tool, WBN-CBN composite tool, and WC-Co alloys. In their review paper, Ezugwu (1997) mentioned that WC-Co grades of cemented carbide and polycrystalline diamond were the best tool materials to machine Ti.

The coated tools performed well during the low cutting speed, but the wear of uncoated tools was severe under all cutting conditions. Coated drills suffered less damage which suggested that the hard coating material protected the tool and substantially reduced the wear rate of the substrate (Sharif and Rahim, 2007).

Effects of coolant

Because the thermal properties of Ti are poor, use of cutting fluids (or coolant) is very important to improve the tool life. Cutting fluids containing phosphates were found to perform better (Machado and Wallbank, 1990, Ezugwu, 1997). Chlorine in cutting fluids might cause stress-corrosion cracking (Kahles et al., 1985). It was also found that sulphur compounds led to sulphur attack on turbine blades made of Ti (Ezugwu, 1997).

Supplying cutting fluids via through-the-drill holes could reduce tool wear by 10 times compared with dry drilling, especially at high cutting speeds (Li et al., 2007).

3.5 Hole diameter and cylindricity in twist drilling

Effects of feedrate and cutting speed

The cylindricity (or roundness) of the drilled holes became worse as the cutting speed and feedrate increased (Kim et al., 2001; Kim and Ramulu. 2004; Kim et al., 2005).

Effects of drill material

Generally, HSS-Co drills had a tendency to produce undersize holes, whereas holes drilled by carbide drills tend to be larger than the drill size (Kim et al., 2001). The amount of oversize increased with increasing feedrate and speed in carbide drilling. This phenomenon could be caused by vibrations induced at higher feedrate and speed (Kim et al., 2001).

3.6 Burr in twist drilling

Effects of feedrate

Lower feedrate produced larger exit burrs. The burr height was proportional to thrust force for a same feedrate (Kim et al., 2001).

Effects of cutting speed

The exit burr heights increased as spindle speed increased. Larger cutting speed, lower feedrate, and longer tool engagement time tended to cause worse burrs (Kim et al., 2001).

Effects of drill geometry and material

Helical point drills produced smaller burrs than split point drills. Both burr height and thickness were reduced by using a larger helix angle or a larger point angle (Dornfeld et al., 1999). Carbide drills generally produced smaller exit burrs than HSS-Co drills did (Kim et al., 2001).

Effects of coolant

Dornfeld et al. (1999) observed four distinct burr types in dry drilling and three burr types in wet drilling of Ti. The exit burrs without cutting fluids were substantially larger.

3.7 Surface roughness in twist drilling

Effects of feedrate

The most important factor on roughness was found to be cutting speed for HSS-Co drills, feedrate for carbide drills. For both drill materials, the increased feedrate produced higher surface roughness (Kim and Ramulu, 2004; Kim et al., 2005). The combination of high feedrate and high speed could produce visible hole damage (Kim and Ramulu, 2005a; Ramulu et al., 2001).

Effects of cutting speed

Cutting speed had a significant influence on surface roughness when drilling Ti (Kim and Ramulu, 2004). When using carbide drills, higher cutting speeds could produce lower surface roughness (Rahim and Sharif, 2006; Sharif and Rahim, 2007). However, Kim and Ramulu (2001) observed that increased cutting speed produced higher surface roughness significantly with HSS-Co drills but not much with carbide drills.

Effects of drill material

Holes drilled by HSS-Co drills had higher surface roughness than those by carbide drills (Kim and Ramulu, 2004, Kim et al., 2001). Coated drills produced lower surface roughness at most cutting speeds when compared to uncoated carbide drills. The wear pattern of these tools might have a great contribution to the roughness difference, since the tool wear rate of coated drills was much lower than that of uncoated drills (Sharif and Rahim, 2007).

3.8 Chip type in twist drilling

Effects of feedrate

The chip type was dependant on feedrate in twist drilling. Ti chips formed at low feedrate were long and continuous, and became shorter and stiffer as the feedrate increased (Kim and Ramulu, 2005a; Kim et al., 2005; Yang and Liu, 1999).

Effects of cutting speed

Komanduri and Turkovich (1981) analyzed data from high and low speed tests and explained the catastrophic shear failure mode of chip formation and the influence of process parameters. Brown and Hinds (1985) found that increased cutting speed would enhance the chip serration frequency.

Effects of other factors

Another factor affecting Ti chip formation was microstructure. The conditions of segmentation varied according to the microstructure. For example, no conspicuous serrated chip was observed in α alloys, however, typical serrated chip could be observed in α-β alloys and more adiabatic shear deformation occurred to form one chip serration in β alloys (Motonishi et al., 1987).

Drilling temperature has also been investigated as a factor having direct effects on Ti chip formation. Dillon et al. (1990) reported the smallest Ti chips at a workpiece temperature of no more than 190ºC.

3.9 Theoretical study and modeling on twist drilling

Lambert (1979a) brought forth a model to predict the thrust force and torque from drilling variables (cutting speed, feedrate) and drill geometry (point angle and relief angle). He also studied the cost optimization of drilling Ti/composite stacks (Lambert, 1979b) to form a model to predict tool life, maximum torque, maximum thrust, hole diameter, surface roughness, and production cost per part. His method combined statistically designed experiments, non-linear regression analysis, and a powerful optimization tool – geometric programming. The feasibility of the techniques described was demonstrated.

Li et al. (Li, 2007, Li and Shih, 2007) conducted finite element modeling of Ti drilling. In the model, the chisel and cutting edges of a spiral point drill were treated as a series straight-cutting-edge elementary cutting tools with various rake and inclination angles. The cutting forces and material deformation of each elementary cutting tool were studied by drilling with and without internal cutting fluid supply. As a result, the thrust force and torque predicted by the finite element model matched well with experimentally measured values. The model also enabled better understanding of the work material deformation and drill temperatures and stresses.

Kim and Ramulu (2004) conducted a modeling of Ti drilling in terms of hole quality, tool life, and process cost. A quadratic response surface model was used to predict the drilling hole quality as a function of the main effects of factors, their interactions, and their quadratic components. An empirical equation was established to predict tool life. Cutting speed and feedrate were the two variables in the equation. An exponential equation was established to predict the process cost of Ti drilling based on the minimum production time and cost per hole criteria. They also developed functions to evaluate solution alternatives according to multiple criteria, because Ti was often drilled as a part of dissimilar materials. They later proposed a model for maximum thrust and torque when drilling Ti/graphite stacks (Kim et al., 2005).

4. Vibration assisted twist drilling

<u>4.1 Description and features of vibration assisted twist drilling</u>

Vibration assisted drilling uses superimposed vibration to the twist drill or the workpiece during the drilling operation. The continuous, homogeneous motion of the drill's cutting edges along a helix with an axial sinusoidal oscillation is overlaid due to the additional application of ultrasonic vibration.

Fig. 7 illustrates vibration assisted twist drilling. For the setup used by Okamara et al. (2006), the drilling spindle was mounted on a linear motor for low-frequency vibration in the axial direction. Vibration amplitude and frequency were variable, and the vibration amplitude was large enough to realize the intermittent cutting in combination with the setting of feedrate.

The most important issue of vibration assisted drilling is how to create the desired vibration. Many researchers have investigated the issue (Adachi et al., 1987; Chern and Lee, 2006; Jin and Murakawa, 2001; Onikura et al., 1996; Takeyama, 1991). Since 1970s, vibration drilling has been employed in the precision drilling of wood (Kumabe and Sabuzawa, 1971) and low carbon steel (Kumabe and Sabuzawa, 1972). Both theoretical investigations and experimental results indicate that the quality of the drilled holes could be improved, and the thrust force reduced by vibration assistance (Wang and Qiu, 1989; Wang and Wang, 1998; Takeyama, 1991; Zhang and Feng, 1994).

Vibration assisted twist drilling includes low-frequency and ultrasonic vibration assisted drilling. Ultrasonic vibration assisted drilling has the effects of increasing the rigidity of the drill, reducing the extent of drill skidding and hole size errors, and increasing the tool life. Low frequency vibration assisted drilling could affect chip shape (Kim and Choi, 1997; Kumabe, 1979; Zhang and Wang, 1998).

4.2 Cutting force in vibration assisted twist drilling

Compared with conventional twist drilling, the maximum thrust force was higher with vibration assisted twist drilling but the average thrust force was much lower, as shown in Fig. 8. In vibration assisted twist drilling, the maximum thrust force increased when using low-frequency vibration. However, when the vibration frequency was above 20 kHz, the measured thrust force (both maximum and average values) with vibration was lower than that without vibration (Okamura et al., 2006).

4.3 Tool wear in vibration assisted twist drilling

Okamura et al. (2006) compared the drill flank wear and the chipping on chisel edge between drilling processes with and without vibration. The drill wear rate was reduced to about 1/3 and the chipping on chisel edge of the drill was eliminated when low-frequency vibration was applied. They attributed this result to the decrease of drilling temperature and some lubrication effect caused by the vibration.

4.4 Burr in vibration assisted twist drilling

Both height and thickness of the hole exit burr became smaller with vibration assisted twist drilling. The possible reason is that the lower drilling temperature might prevent the increase of material ductility (Okamura et al., 2006; Sakurai et al., 1992).

4.5 Chip formation in vibration assisted twist drilling

Chips produced in vibration assisted twist drilling were short and had a conical helix shape, and hence were thought to be effective to reduce adhesion and jamming. Higher vibration frequency would produce shorter chips desirable for ejecting. The increase of vibration amplitude would help to generate better chip shape (more conical helix) (Okamura et al., 2006).

5. Ultrasonic machining (USM)

5.1 Description and features of USM

Ultrasonic machining (USM), as illustrated in Fig. 9, has also been called ultrasonic drilling, ultrasonic abrasive machining, ultrasonic cutting, ultrasonic dimensional machining, and slurry drilling (Thoe et al., 1998). In this process, low-frequency electrical energy is converted to a high-frequency electrical signal which is converted into mechanical vibrations by a transducer (Perkins, 1972; Scab, 1990; Thoe et al., 1998). This causes the tool to vibrate along its longitudinal axis at high frequency (usually ≥ 20 kHz) with an amplitude of 5-50 μm (Kennedy and Grieve, 1975; Thoe et al., 1998). A controlled static load is applied to the tool, and abrasive slurry (comprising water and small abrasive particles) is pumped around the cutting zone (between the tool tip and the workpiece) to impact the workpiece surface causing material removal by micro chipping (Thoe et al., 1998). Important parameters that have been studied in USM of Ti include vibration amplitude and the abrasive particle size in the slurry.

Holes as small as 76 μm in diameter can be machined with USM. However, the depth to diameter ratio is limited to about 3:1 (Kobls, 1984). The disadvantages of USM are lower material removal rate (MRR) compared with other processes and serious tool wear that usually affects machining precision (Lin et al., 2000). Unlike twist drilling, only very small debris was produced during the USM process. So USM does not have the problem of chip ejection so it helps to improve the hole quality when drilling Ti (Singh and Khamba, 2006).

5.2 Tool wear in USM

Singh and Khamba (2006) discussed the effects of some USM process parameters on the tool wear. Ultrasonic power had a significant influence on tool wear, however, the results were different for different Ti materials. Increasing ultrasonic power exacerbated the tool wear rate for some Ti alloys but could have a saddle effect on the tool rate when drilling some other Ti alloys. The vibration amplitude of the tool also affected the tool wear rate. Smaller amplitude was better for reducing abrasive wear and increasing the tool life (Kops, 1964; Neppiras, 1956; Rozenberg and Kazantsev, 1964; Weller, 1984).

5.3 Surface roughness in USM

The only parameter affecting the surface roughness mentioned in the literature is the abrasive grain size of the slurry (Singh and Khamba, 2007). Lower surface roughness was attained with smaller abrasive particles in the slurry.

6. Rotary ultrasonic machining (RUM)

6.1 Description and features of RUM

Rotary ultrasonic machining (RUM) is a hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining (Pei et al., 1995). Fig. 10 is a schematic illustration of RUM. The cutting tool is a core drill made of metal-bonded diamond abrasives. The rotating tool is ultrasonically vibrated and fed toward the workpiece at a constant feedrate (or pressure). Meanwhile, coolant is pumped through the hole in the middle of the drill.

Important process parameters are feedrate, spindle speed (cutting speed), and ultrasonic power (which controls the amplitude of ultrasonic vibration), diamond size and concentration, bond type, and tool geometry.

6.2 Cutting force in RUM

The cutting force measured in RUM of Ti was the maximum cutting force, as shown in Fig. 11. It was 20% lower than that when ultrasonic vibration was turned off (when the vibration is turned off, the RUM process becomes a diamond drilling process with a core drill (Churi et al., 2006; Churi et al., 2007). Cutting force became lower with higher spindle speed, lower feedrate, and medial range of ultrasonic power (Churi et al., 2006), as shown in Fig. 12. The presence of slots in the tools reduced cutting force by 7%. Fig. 13 shows cutting tools with and without slots. Cutting force could be lower with smaller diamond abrasive size (larger mesh #), higher diamond concentration, and bond type B, as shown in Fig. 14.

6.3 Tool wear in RUM

Churi et al. (2005; 2006; 2007) made the comparison of the tool wear rate between the rotary ultrasonic machining and diamond drilling of Ti, and investigated the effects of cutting tool variables on tool wear. They found that, compared with diamond drilling process, the tool wear rate with RUM was about 85% lower. The tool wear rate can be reduced by changing the parameters of cutting tool. Lower tool wear rate was obtained when using larger diamond abrasives size, lower diamond concentration, and bond type B (Churi et al., 2007), as shown in Fig. 15.

6.4 Surface roughness in RUM

After RUM of Ti, two parts can be obtained: a rod and a hole, as shown in Fig. 16. Normally, the desired hole is of the most concern. Surface roughness was measured on the hole surface (Churi et al., 2006; Churi et al., 2007). Lower surface roughness was obtained with RUM than with diamond drilling. Higher spindle speed, lower feedrate, and higher ultrasonic power are helpful to reduce the surface roughness, as shown in Fig. 17. Different cutting tools of RUM also have a significant influences on surface roughness. Smaller abrasive grit size, lower diamond concentration, and bond type C could reduce surface roughness (Churi et al., 2005; Churi et al., 2006; Churi et al., 2007), as shown in Fig. 18.

7. Concluding remarks

Mechanical drilling processes for Ti include twist drilling, vibration assisted twist drilling, ultrasonic machining (USM), and rotary ultrasonic machining (RUM). Table 1 provides an overview of reported investigations on these processes. Twist drilling has been studied the most among all the mechanical drilling processes for Ti. In contrast, none of other three processes has been studied to the similar extent.

Twist drilling has been the predominant process for Ti drilling in aircraft manufacturing. However, manufacturing cost with twist drilling has been high due to low tool life and/or long cycle time. Especially for newer generations of aircraft, use of Ti/composite stacks presents new challenges to twist drilling, since composites tend to wear twist drills much faster than Ti alone. Cost-effective drilling processes for Ti are desirable.

There are no reports on manufacturing applications of ultrasonic machining (USM) or rotary ultrasonic machining (RUM). Reasons for the lack of production applications of these processes might be: (1) delivery of slurry (necessary for USM) to the cutting zone may become very difficult for horizontally-oriented holes, and (2) it may be too difficult to make portable units for these processes (but portable units are needed for many drilling operations in aircraft manufacturing (Waurzynia, 2002).

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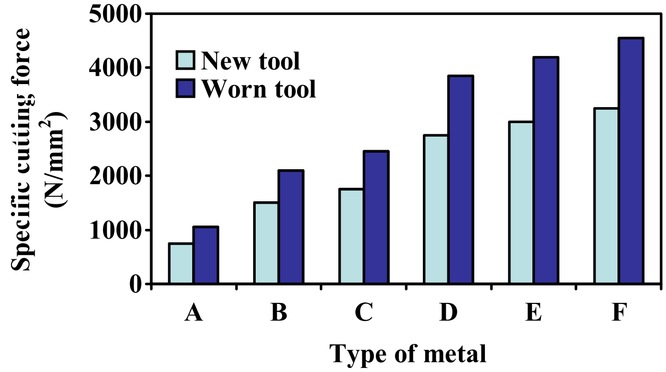
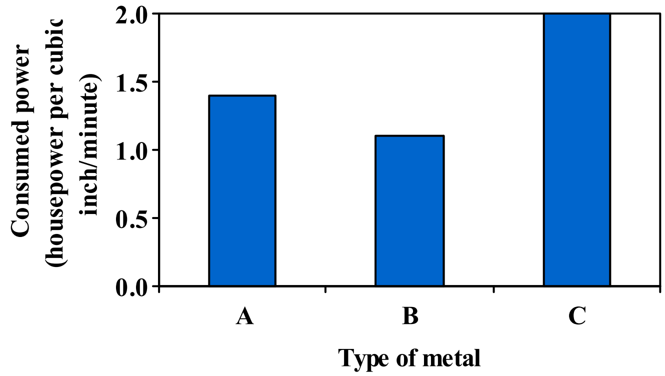


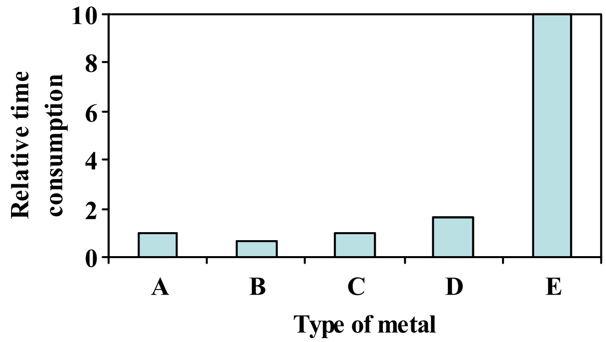
A: Aluminum alloy
B: Cast iron
C: Titanium alloy
D: Stainless steel
E: Nickel-based alloy
F: 60HRC steel

Fig. 1. Specific cutting force when drilling different metals (after (Anonymous 2006)).



A: Steel
B: Ti
C: Nickel-based alloy

Fig. 2. Consumed power when drilling different metals (after (Kahles et al., 1985)).



A: Steel
B: Commercially pure titanium
C: Ti-8Al-1Mo-1V
D: Ti-6Al-4V
E: Ti-13V-11Cr-3Al

Fig. 3. Time consumption of drilling different metals (after (Yang and Liu, 1999)).

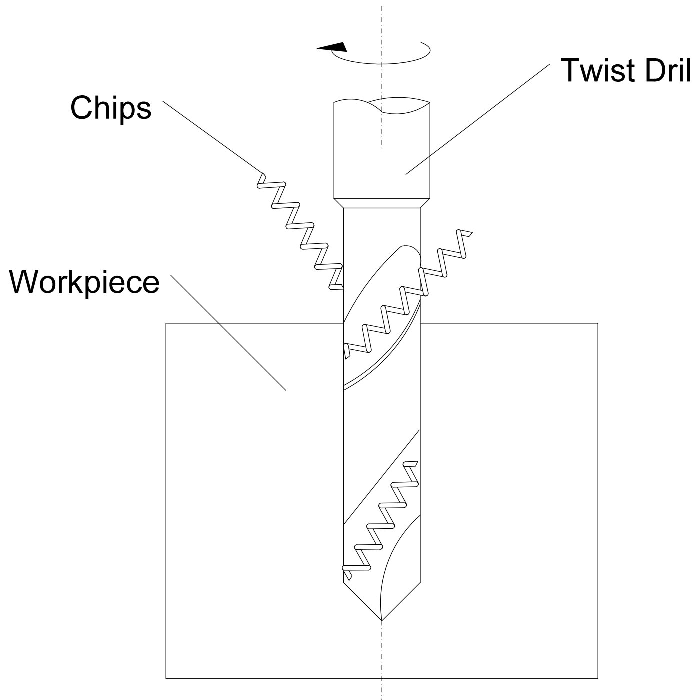


Fig. 4. Illustration of twist drilling (after (Anonymous 2008)).

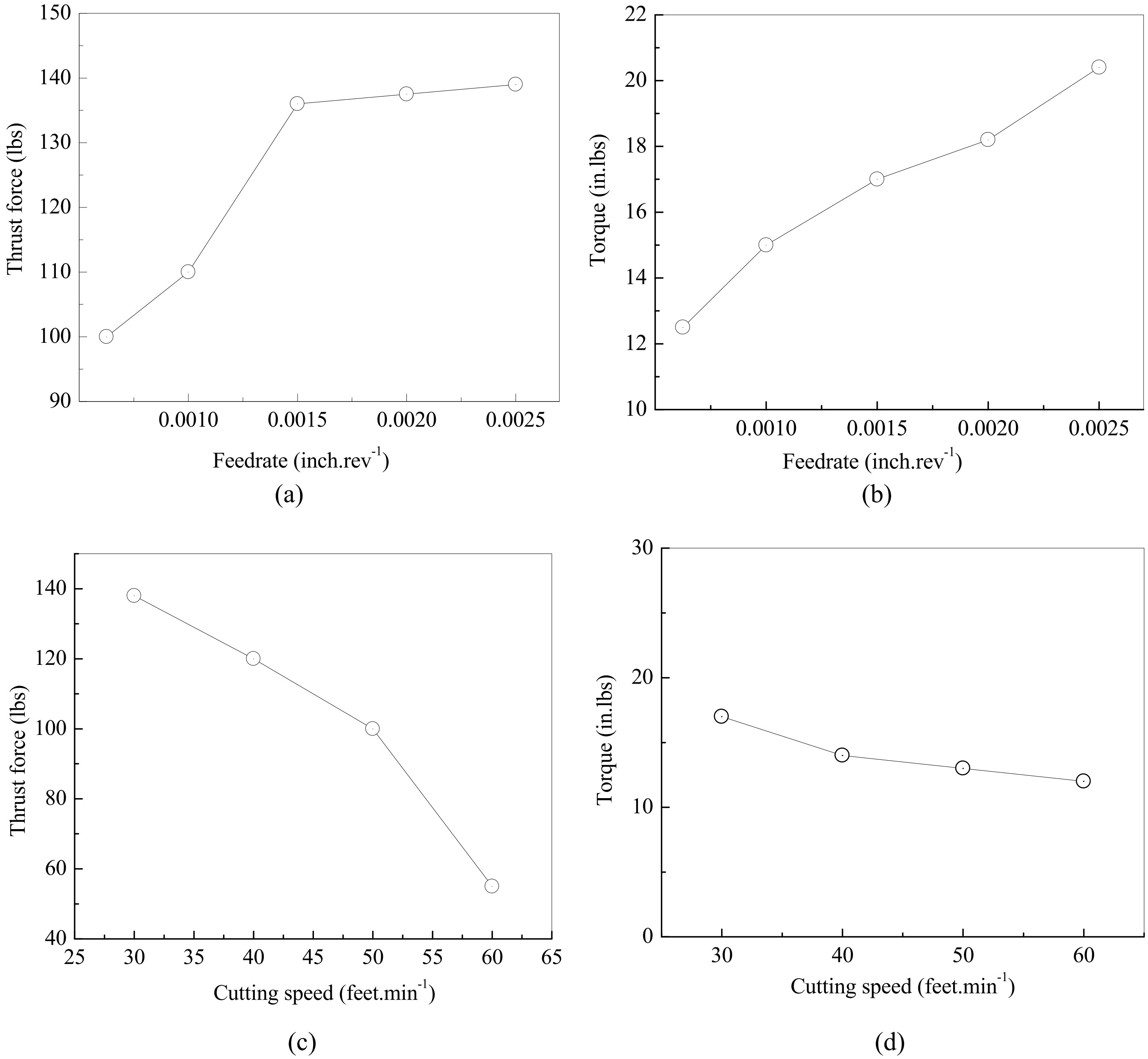


Fig. 5. Effects of process parameters on thrust force and torque (after (Lambert 1979a)).

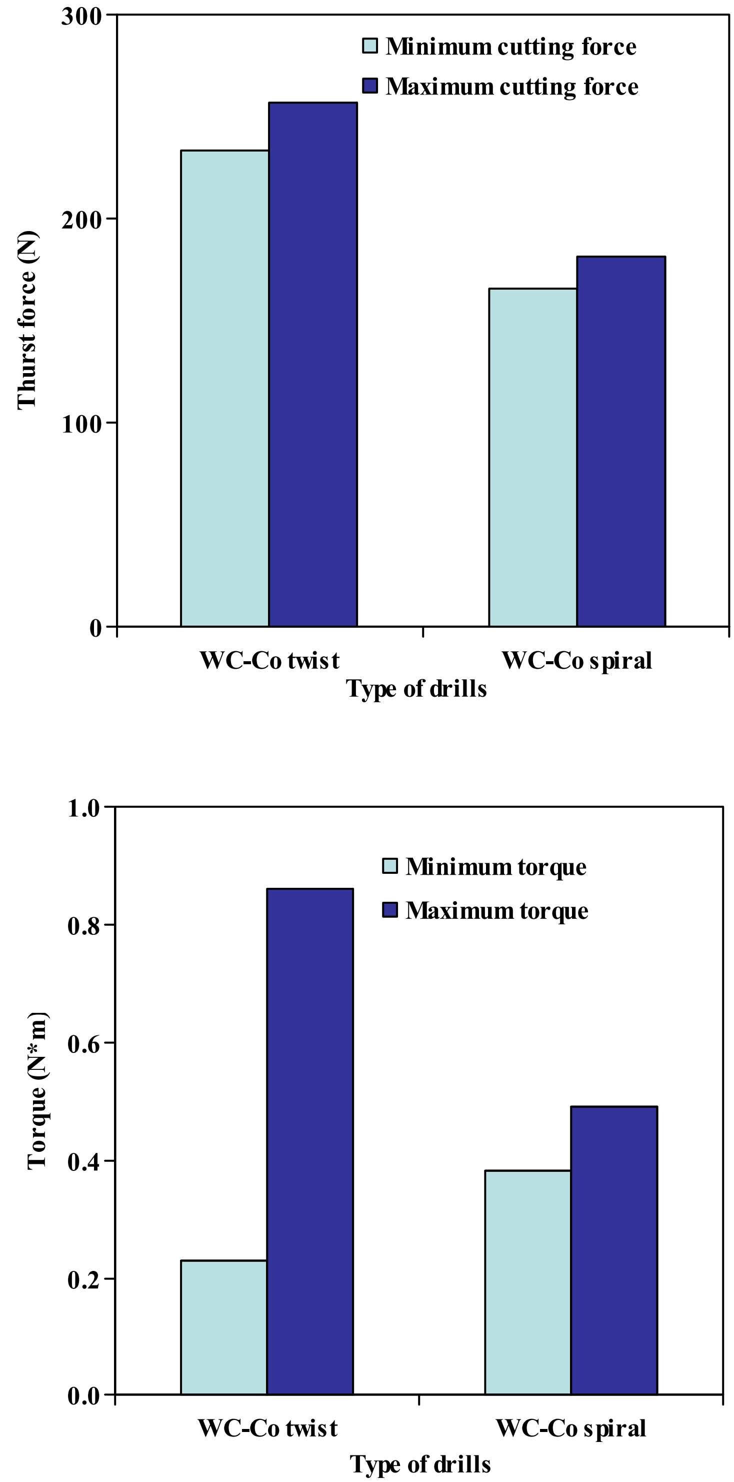


Fig. 6. Thrust force and torque with different drills in Ti drilling (after (Li et al., 2007)).

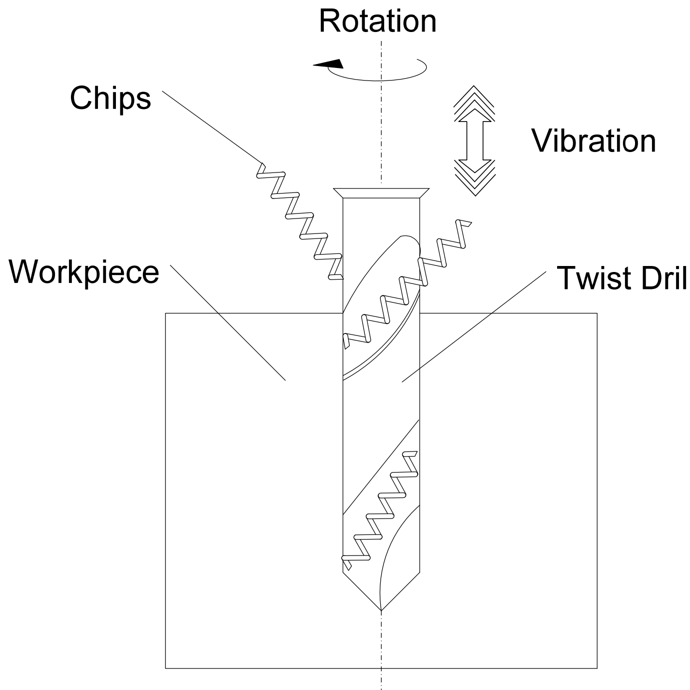


Fig. 7. Schematic of vibration assisted twist drilling (after (Okamura et al., 2006)).

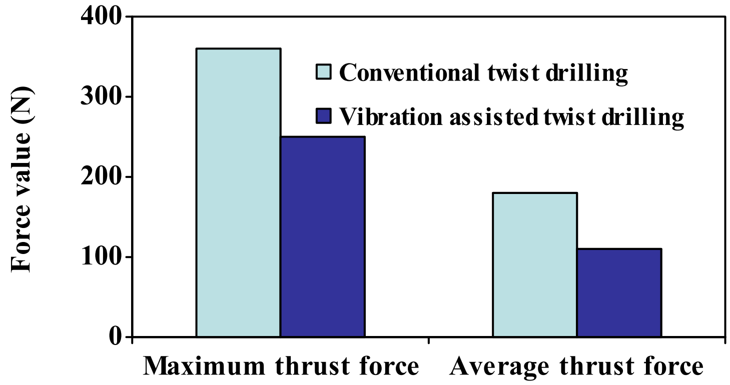


Fig. 8. Thrust force comparison between twist drilling and vibration assisted twist drilling of Ti (after (Okamura et al., 2006)).

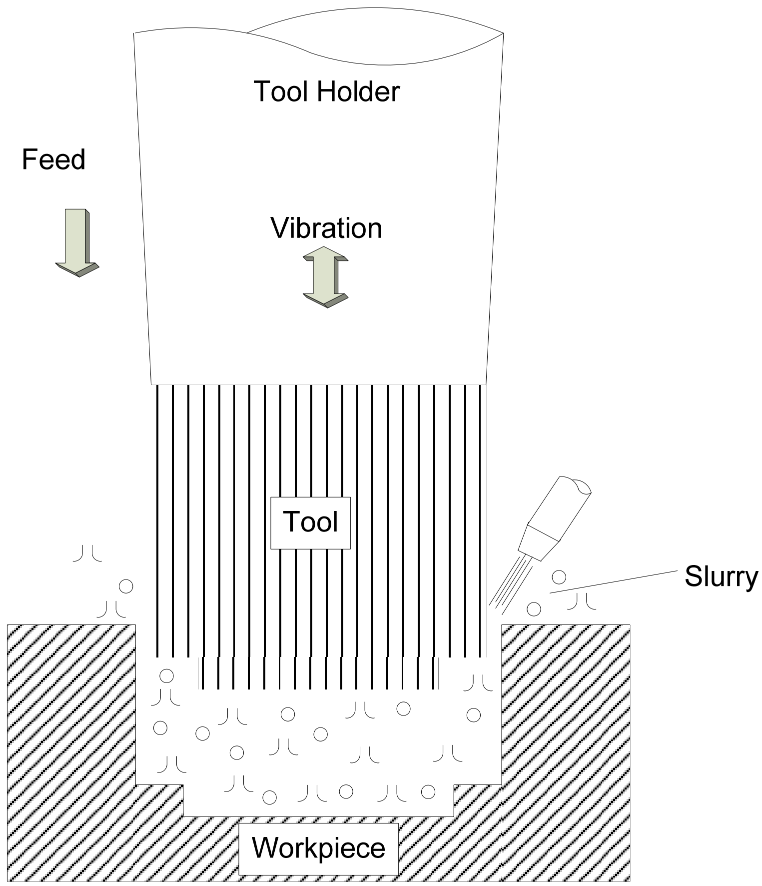


Fig. 9. Schematic of ultrasonic machining (USM) (after (Singh and Khamba, 2006)).

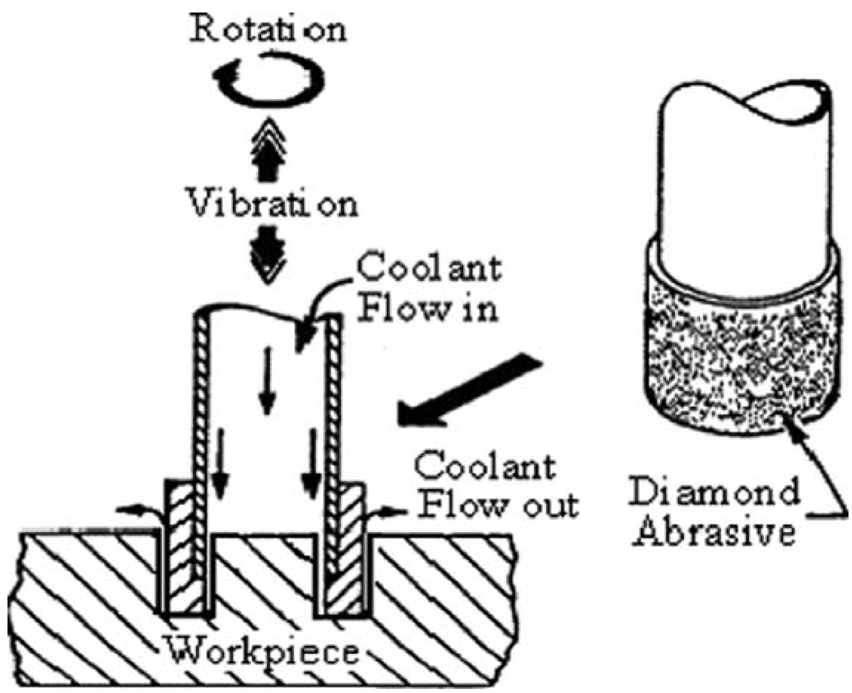


Fig. 10. Schematic of rotary ultrasonic machining (RUM).

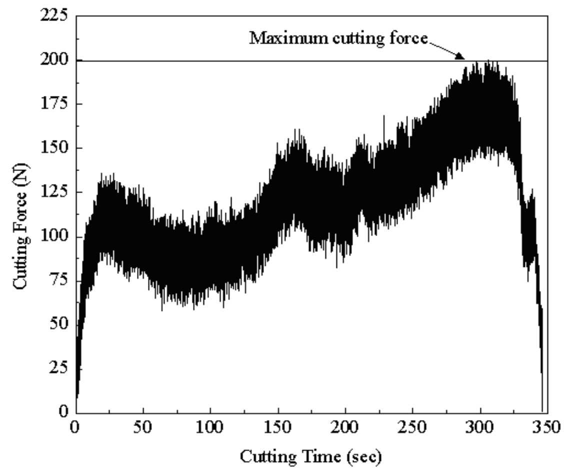


Fig. 11. Measurement of maximum cutting force in RUM of Ti.

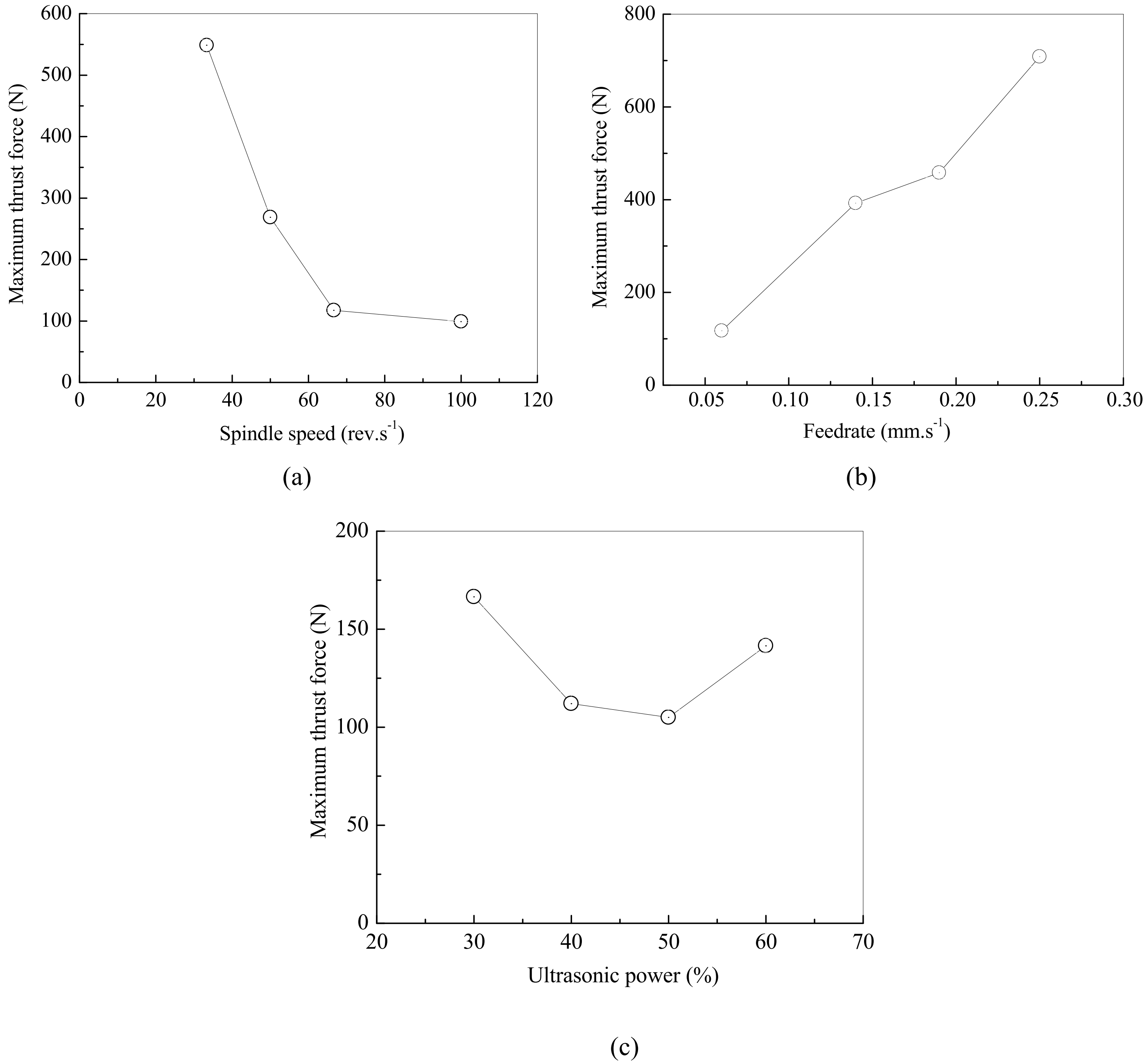
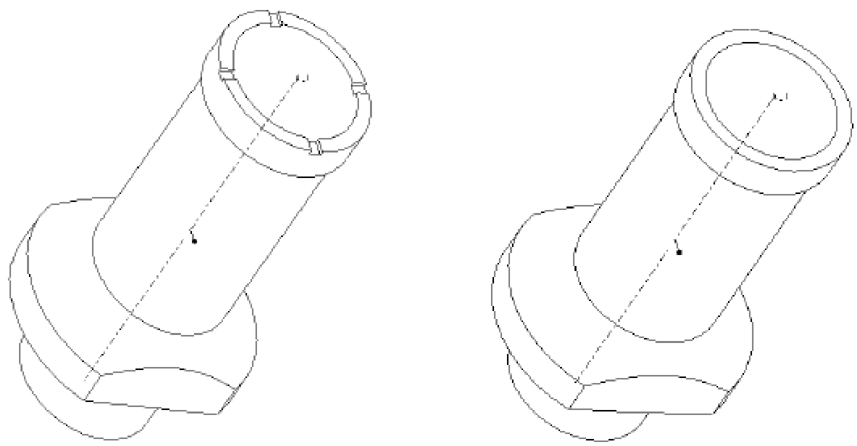


Fig. 12. Effects of process parameters on thrust force in RUM of Ti (after (Churi et al., 2006)).



(a) With slots (b) Without slots

Fig. 13. RUM cutting tools with and without slots.

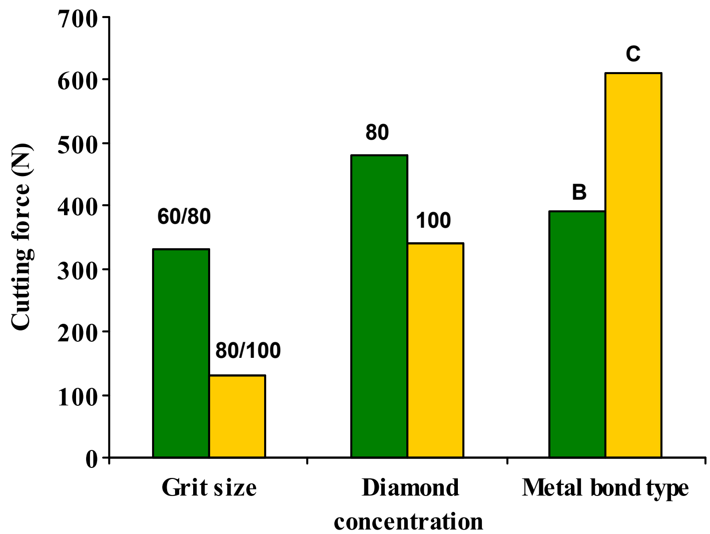


Fig. 14. Relationship between tool parameters and cutting force in RUM of Ti (after (Churi et al., 2007)).

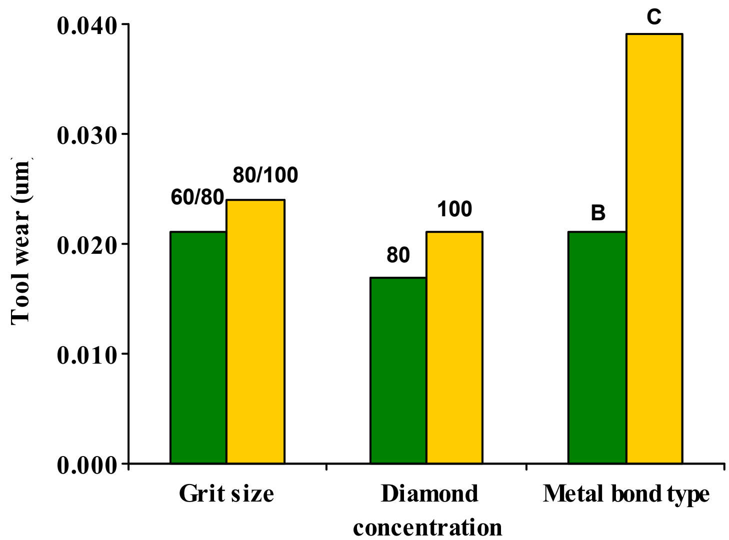


Fig. 15. Relationship between tool parameters and tool wear in RUM of Ti (after (Churi et al., 2007)).

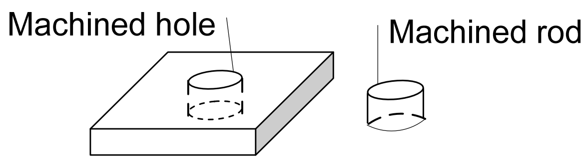


Fig. 16. Hole and rod machined by RUM.

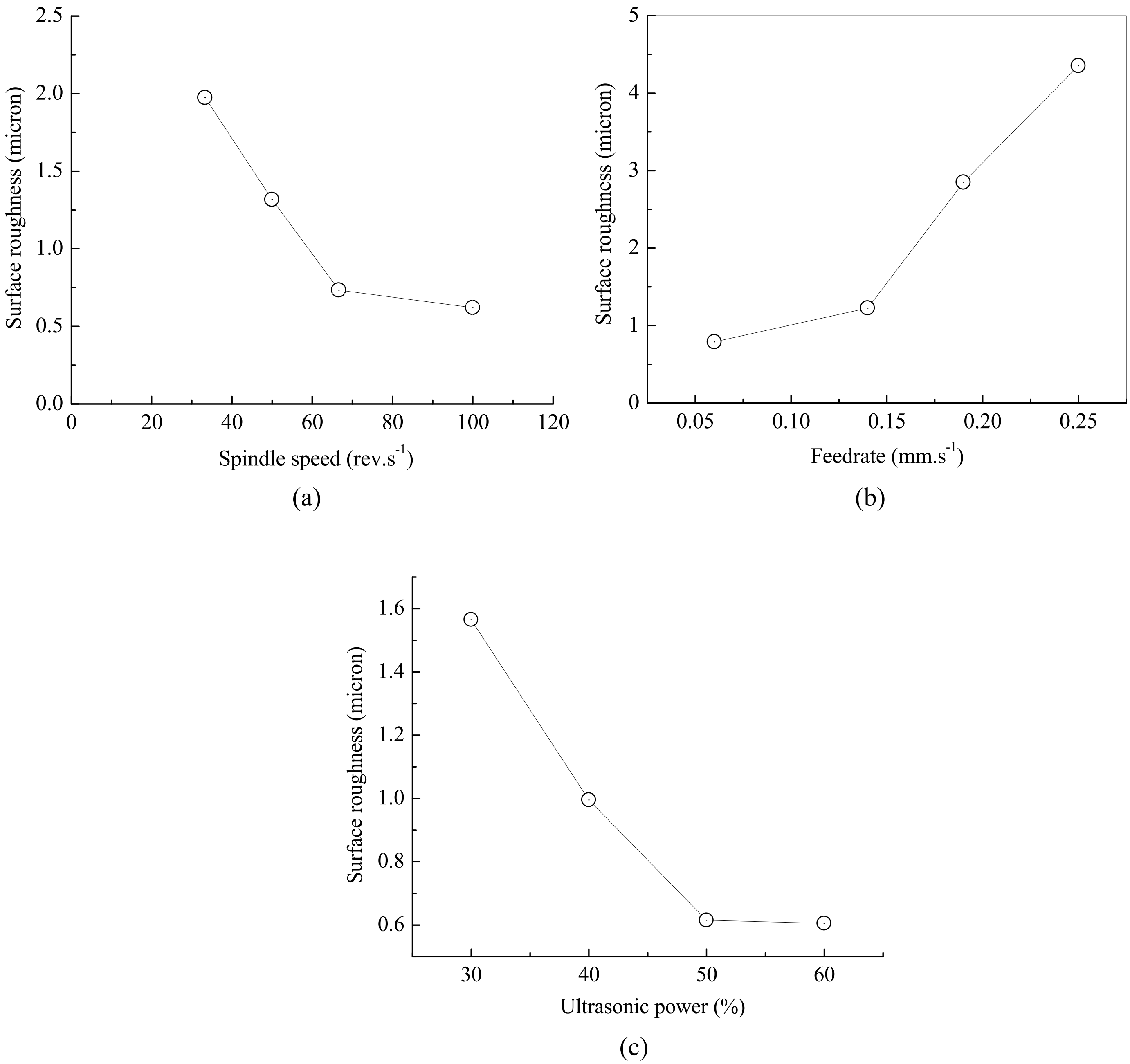


Fig. 17. Relationship between process parameters and surface roughness in RUM of Ti (after (Churi et al., 2006)).

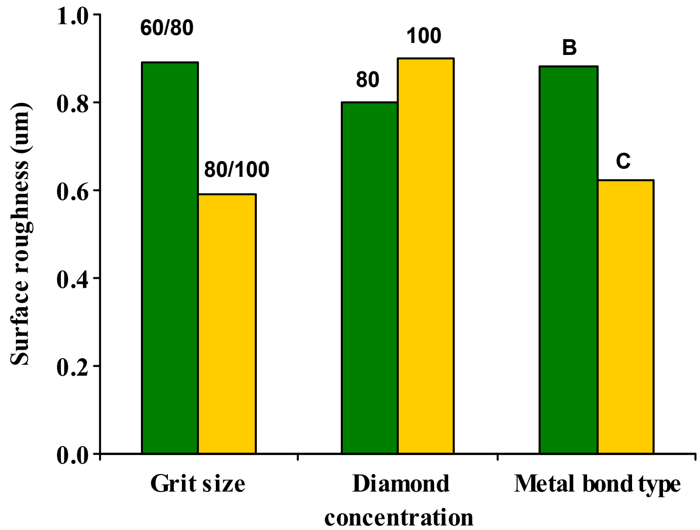


Fig. 18. Relationship between tool parameters and surface roughness in RUM of Ti (after (Churi et al., 2007)).

Table 1 Overview of reported investigations on Ti drilling processes

	Twist drilling	Vibration assisted twist drilling	Ultrasonic machining	Rotary ultrasonic machining
Cutting force	(Anonymous, 2008; Colligan, 1994; Drozda and Wick, 1983; Ezugwu, 1997; Kahles et al., 1985; Kim and Ramulu, 2005a; Kim and Ramulu, b; Kim et al., 2001; Konig, 1979; Lambert, 1979a; Li, 2007; Li et al., 2007; Rahim and Sharif, 2006; Ramulu et al., 2001; Rao et al., 1990; Yang and Liu, 1999; Zhu and Wang, 2006)	(Okamura et al., 2006)		(Churi et al., 2005; Churi et al., 2006; Churi et al., 2007)
Cutting temperature	(Bayoumi and Xie, 1995; Brown and Hinds, 1985; Ezugwu, 1997; Konig, 1979; Li 2007; Rahim and Sharif, 2006; Shahan and Taheri, 1993)			
Tool wear	(Aust and Niemann, 1999; Barish, 1988; Brown and Hinds, 1985; Dearnley and Grearson, 1986; Dornfeld et al., 1999; Ezugwu, 1997; Hartung and Kramer, 1982; Kahles et al., 1985; Li et al., 2007; Machado and Wallbank, 1990; Narutaki and Murakoshi, 1983; Rahim and Sharif, 2006; Rao et al., 1990; Sharif and Rahim, 2007; Trucks 1987; Yang and Liu, 1999; Zhu and Wang, 2006)	(Okamura et al., 2006)	(Kops, 1964; Neppiras, 1956; Razenberg and Kazantsev, 1964; Singh and Khamba, 2006; Weller, 1984;)	(Churi et al., 2005; Churi et al., 2006; Churi et al., 2007)
Surface roughness	(Child and Dalton, 1965; Kim and Ramulu, 2004; Kim and Ramulu, 2005a; Kim et al., 2001; Kim et al., 2005; Konig and Schroder, 1975; Rahim and Sharif, 2006; Ramulu et al., 2001; Sharif and Rahim, 2007)		(Singh and Khamba, 2007)	(Churi et al., 2005; Churi et al., 2006; Churi et al., 2007)
Diameter and cylindricity	(Kim and Ramulu, 2004; Kim et al., 2001; Kim et al., 2005)			
Burr	(Dornfeld et al., 1999; Kim et al., 2001)			
Chip type	(Dillon et al., 1990; Kim and Ramulu, 2005a; Kim et al., 2005; Li et al., 2007; Motonishi et al., 1987; Komanduri and Turkovich, 1981; Yang and Liu, 1999)	(Okamura et al., 2006)		