Title: AN APPARATUS FOR AND A METHOD OF TURNING DIFFICULT-TO-CUT ALLOYS

Figure 2

Abstract: The present invention discloses high frequency vibration assisted turning apparatus and method for Ti alloy work pieces. The invention is also applicable to alloys that are hard to machine in general. It is a novel manufacturing technology, where high frequency vibrations are imposed on the conventional movement of the cutting tool. As an example frequency of 20 kHz and amplitude of 20 µm are provided to the cutting tool in the direction of feed given to tool holder. The method results in reduction of shear friction at the contact between the tool and the work piece, which in turn results in the reduction in shear band formation in this high frequency assisted turned chips. There are benefits which results in terms of improved chip mechanism and tool life. It is observed that the High Frequency Turning produces a better surface finish than the conventional methods.
— as to the applicant's entitlement to claim the priority of
the earlier application (Rule 4.17(iii))
— of inventorship (Rule 4.17(iv))

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An Apparatus For and A Method Of Turning Difficult-to-Cut alloys

Field of Invention
The present invention relates to machining processes in the manufacturing industry. In particular, the invention relates to an apparatus for and a method of turning difficult-to-cut alloys for example Titanium alloys using vibrations of a frequency higher than human hearing for example ultrasonic vibration.

Background of invention
Modern hi-tech industries such as aerospace have recently witnessed developments like reduction in aircraft weight and increase in aircraft speed. These have resulted in tremendous increase in the use of Titanium and its alloys. However, the process of conventional turning (CT) of Ti alloys is complex, mainly due to high machining heat generation and subsequent rapid wear of cutting edges during machining.

Presently, the machining of Ti alloys, or that of alloys that are hard to machine, is carried out using CT or the so called non-conventional methods which include Electrical Discharge Machining (EDM) and laser beam machining. Hereafter Conventional Turning will be referred as CT.
In conventional machining of Ti alloys, concentration of heat on cutting edge and tool face, serrated chip formation, cutting force fluctuations, causes poor dimensional accuracy. Similarly, non-conventional machining processes have limitations during machining of Ti alloys such as poor surface finish, formation of heat affected zone on machined surface, etc. In the case of conventional turning, as titanium alloy is chemically active, it causes the chips to adhere to the tool tip, especially at the high temperatures that result from the machining process at the contact between the tool tip and the component being machined. This leads to formation of a built-up edge (edge formed with the material that builds up on the tool). Accordingly, when the adhered chips separate from the tool tip, a part of the tool material is removed from it causing severe wear. Also, the chip entangles between tool and work piece which results in damage to the surface of work piece, resulting in an increased surface roughness of the machined surface.

There is therefore a need to provide a process of turning for difficult-to-cut alloys such as Ti alloy work pieces which would overcome the above drawbacks.

The present invention relates to improving machinability of Ti6AlV using High Frequency vibrations to the cutting tool during turning. This machinability is measured using chip mechanism study, surface topography, etc. Some publications related to High Frequency vibration assisted machining are studied and discussed here.
1. A US patent publication no. US8205530 B2, 2013 related to Processes for improving tool life and surface finish in high speed machining of difficult to cut materials. A frequency of around 500 kHz and amplitude of 15 µm is used for experimentation.


**Objects of invention:**

Accordingly, one object of the present invention is to provide an apparatus for turning Ti alloy work pieces, which uses vibrations of frequency higher than human hearing.

Accordingly, one object of the present invention is to provide vibrations assisted method (Frequency range 15kHz to 25kHz) of turning Ti alloy work pieces (direction of vibration - in feed) which will provide a superior surface finish measured in terms of chip mechanism, surface topography, and chip microstructure.

Another object of the invention is to provide a method of turning Ti alloy work pieces which would reduce:
- Serrated chip formation
- Concentration of heat on the cutting edge and tool face
- Cutting force fluctuations
- Dimensional inaccuracy
- Adherence of chips to tool tip
- Wear of tool tip
- Chip entanglement between tool and work piece and damage to surface of work piece therefrom

The overall advantages of the method of invention are:
- an improvement in the dynamic cutting stability.
- a reduction in the cutting forces and improvement in tool life.
- a reduction in surface roughness of machined surface.
- a reduction in residual stresses in machined work piece.
- a reduction in cutting temperature.

Summary of invention:
The present invention discloses high frequency vibration assisted turning apparatus and method for Ti alloy work pieces. The invention is also applicable to alloys that are hard to machine in general. It is a novel manufacturing technology, where high frequency vibrations are imposed on the conventional movement of the cutting tool. As an example-frequency of 20 kHz and amplitude of 20 \( \mu \)m are
provided to the cutting tool in the direction of feed given to tool holder. The method results in reduction of shear friction at the contact between the tool and the work piece, which in turn results in the reduction in shear band formation in this high frequency assisted turned chips. There are benefits which results in terms of improved chip mechanism and tool life. It is observed that the High Frequency Turning produces a better surface finish that the conventional methods.

List of parts

1. Work piece holder (a chuck)
2. Work piece
3. Insert (or a tool)
4. Horn
5. Tool assembly holder
6. Concentrator
7. Piezoelectric transducer
8. Electric signal generator

Brief Description of Drawings

Figure 1 shows Geometry and meshing of the workpiece and cutting tool

Figure 2 shows Movement control for the cutting tool during HFT

Figure 3 shows Effect of shear friction (m) on cutting forces for HFT

Figure 4 shows Effect of shear friction (m) on thrust forces for HFT
Figure 5 shows Machined surface (High frequency and conventional)

Figure 6 shows Effect of an increase in the cutting speed on average surface roughness.

Figure 7 shows Comparative nano-indentation analyses of surface layers of Ti-6Al-4V after conventional and High Frequency turning

Figure 8 shows Effect of increase in cutting speed on chip length per softening

**Description of the invention**

The present invention discloses a High frequency assisted turning (HFT) apparatus and method for Ti alloy work pieces. The invention is also applicable to alloys that are difficult to machine in general. The materials with the properties such as low thermal conductivity, high chemical reactivity, high strength and low elastic modulus can be considered to be difficult-to-machine alloys. This include family of Titanium alloys, including alpha rich and beta rich and alpha + beta titanium alloys along with super alloys like Inconel, Hatelloy, Waspelloy etc. Hereafter High Frequency Turning is referred as HFT.

Figure 1 shows a schematic of the apparatus of the present invention also called High Frequency vibrating tool assembly. The set up consists of High Frequency generator, a piezoelectric transducer (or converter) to convert the electrical signal from generator to mechanical vibrations, a booster to boost these vibrations (since the amplitude of vibrations could be very small at the face of the transducer). The
vibrations are carried to the cutting tool tip using a horn. The assembly is typically mounted on a jig plate (made of mild steel or any other suitable material) with three supports mounted on it which holds the tool assembly at proper places. The assembly operates in a dry machining mode.

Frequency of vibration is in the range of 15 to 25 kHz and the amplitude 10 to 40 μη. The work piece holder (chuck) is capable of allowing the work piece to rotate at required rotational speed. The tool assembly holder feeds the tool onto the work piece in a direction perpendicular to the rotational plane of the work piece. The tool vibrates longitudinally and makes intermittent contact with the work piece.

A concentrator/booster is provided to boost vibrations received from transducer. This is because the amplitude of vibrations at the face of the transducer is very small and need to be amplified as they are carried to the cutting tip using a horn or tool holder. The horn may be in the form of a long rod made of Titanium on which an insert (tool) is mounted, a tool assembly holder, a concentrator, a piezoelectric transducer, an electric signal generator.

The method proposed in the present invention is a method to turn work pieces made from titanium alloys. The method comprises:
- Holding securely the work piece made of Titanium alloy (Ti6Al4V) in the work piece holder

- Rotating the work piece about its central axis.

- Carrying out the turning operation by:

  5  o Transferring electric signal from generator to piezoelectric transducer

  o Converting (using piezoelectric transducer) the electric signal into mechanical vibrations

  o Amplifying mechanical vibrations using the concentrator

  10 o Transferring the amplified vibrations via the horn to the cutting tool insert

  o Holding in a tool holder the entire vibrating assembly comprising the insert (tool), the horn, the concentrator, the piezoelectric transducer, and the electric signal generator

  15 o Bringing the tool holder, by moving it in the direction perpendicular to the plane of rotation of the work piece, in contact with the work piece

  o Maintaining the forward movement of the tool holder while maintaining the vibration of the cutting insert in a direction parallel to the axis of rotation of the work piece, thereby maintaining an intermittent contact between the work piece and the tool insert

  20
The invention was verified with finite element simulation and validated with experimental studies.

Simulation:

Simulation analyses were carried out to measure the effectiveness of the apparatus and the method of invention. A 2D FE model was developed in which cutting insert (tool) of tungsten carbide was assumed to be rigid and work piece of Ti-6Al-4V to be plastic.

Fig. 2 shows the high frequency vibrations which were superimposed on the cutting tool by defining the velocity of the cutting tool as a function of time. Fig. 3 and Fig. 4 show the effect of a change in the shear friction constant on cutting force and thrust force during both conventional and High Frequency assisted turning. It was observed that when the shear friction constant is varied from zero to 0.8, there is an average 43% reduction in the required cutting force and an average 48% reduction in thrust force when using FIFT as compared with the CT method.

Experimental studies:

A frequency of 20 kHz and an amplitude of 20 µm was used for the experimentation with the direction of vibration was in feed direction. The
roughness of machined surface was measured in terms of Ra (average surface roughness) during both HFT and CT.

Figure 5 shows the visual difference in both conventional and High Frequency machined surface. High frequency vibration assisted machined surfaces have a matte finish. This suggests that an additional treatment needed on titanium alloy for surgical instruments such as etching, peening and electro-chemical machining can be avoided. However, conventionally machined surfaces have a glossy finish.

The outcomes of the HFT are now discussed in terms of the surface quality, hardness of the machined surface, chip morphology, and the chip microstructure.

**Surface quality:**

Surface finish or quality of a machined work piece is extremely sensitive to changes in the machining process. Hence, it was used as a criterion to identify the special characteristics during both HFT and CT process. It has seen that the tool marks on the machined surfaces are on higher side during CT than HFT.

It is understood that a reduction in contact time between tool and work piece during HFT leads to a change in material deformation process. This reduces the cutting temperature and tool wear, which ultimately improves the surface quality of the deformed work piece. The average surface roughness Ra value measured
for CT surface is 1 µm and that for HFT surface it is 0.6 µm. Thus, 40% reduction in surface roughness is observed for HFT the surface than the CT surface.

It was observed that during the HFT process, material is removed such that it produces 'fish scale' like structure on the surface. The high frequency vibrations form a vibro-impact process, which increases the dynamic stiffness of the lathe-tool-work piece system as a whole and improves the accuracy of turning. Also, due to the intermittent contact between the tool and the workpiece, the temperatures generated during a HFT process are lower than those generated during a CT process (where there's a continuous contact between the tool tip and the work piece). Because of this, combined with the lower speeds at which the HFT operates, the build-up of material (commonly referred to as build-up edge or BUE) on tool surface is avoided during the HFT. As a direct result of this the surface roughness of the work pieces machined using HFT reduces.

It was also observed that the uniformity of the surface finish during HFT depends on the cutting speed. It was found that at a cutting speed of 20 m/min, which is 14% of maximum vibrating velocity of the cutting tip, the HFT process produces the optimal surface finish. The surface finish produced by HFT was also found to be much better than the surface finish produced by the CT. A 40% improvement in surface finish was noted during HFT over that of during CT at a cutting speed of 20 m/min. It was further observed that the reduced tool work piece contact ratio
(TWCR) for HFT also leads to a generation of lower cutting forces, and frictional heat, which resulted into smooth and regular machined surface that is better than that of in CT.

5 **Hardness of the machined surface:**

Figure 7 shows nano-indentation results on surfaces machined using CT and HFT processes.

It was observed that the hardness value of the hardened surface layer for HFT is lower than that of CT. Average hardness value on HFT surface is 3.98 GPa, which is 16% less than the average hardness of CT surface layer i.e. 4.74 GPa. This was due to the fact that grains in CT surface were found to be highly deformed as compared to those in HFT. Another indicator of this was the reduction in shear strain - in the case of HFT grain pattern, a 56% reduction in the shear strain of the deformed grains was observed as compared to CT (maximum measured strain for HFT was 1.27 compared with 2.9 for CT).

**Chip Morphology:**

It is observed that chip thickness measured for CT chip was 132 µm and that for HFT chip was 95 µm. Therefore, an 18% reduction in chip thickness is observed in HFT process over that in CT process.
It was further observed that a continuous interaction between tool and work piece during CT produced thick, uneven chips. However, non-continuous interaction between tool and work piece during HFT produced thin and crack associated chips. The pitch of the chip segment obtained during HFT process was 57 μιη. However, for the chips of CT it was 28 μιη. This leads to an increased chip length per softening for HFT chips.

Further, effects of reduction of temperature on the chip morphology were observed. It was observed that a reduction in cutting temperature during HFT leads to a reduction in thermal softening and hence increases the chip length per softening. It is understood that during CT, with an increase in cutting temperature with the cutting speed the thermal softening increases. It is also known that the chip length is proportional to the softening. At a cutting speed of 30 m/min, the work pieces undergoing both CT and HFT experience higher cutting temperature. Therefore, it was observed that the chip length per softening produced at the speed of 30 m/min was noted to be lower than that produced at 10 m/min and 20 m/min.

For the work piece under consideration, the width of chip segment obtained from HFT process was found to be 48 μιη and that for CT was 26 μιη. Hence, a 44% increase in segment width has been observed for the chips obtained during HFT. Importantly, this increase in segment width leads to a reduction in number of shear bands formed in the chips obtained during HFT. Another important
parameter, the crack angle, for the chips obtained from HFT process was 37 µm and that for CT was 49 µm. Hence, a 23% reduction in crack angle is observed for the chip obtained during HFT. This reduction in crack angle leads to reduced brittleness in the deformation at shear plane during HFT over that of in CT. The included angle for the chips obtained from HFT process was 39.37 µm and that for the CT was 58.3 µm. Hence, a 32% reduction in the included angle is observed for the chips obtained during HFT. This reduction in the included angle leads to a less degree of plastic deformation before fracture during HFT.

Further, it was also seen during HFT process, the chip segmentation does not starts at the edge of the chips as in case of CT but at a distance of 27-70 µm from the chip edge. This shows completely different cutting mechanism for HFT compared to CT which will be beneficial for difficult-to-cut alloys.

For CT chip, shear angle measured at 20 m/min was 16° and that for HFT chip was 34°. This shows that shear angle is higher during HFT, which results into a reduction in cutting forces during HFT than in CT.

**Chip Microstructure**

It is observed that there is very little or no shear band formation in the chips generated during HFT, whereas in CT, a shear band of width 3 µm was observed.
During CT, a reduction in crack length at the machined chip shows smaller intensity of normal stresses on shear plane. However, during HFT large crack appears on the shear plane which shows high intensity of normal stresses. This is also responsible for tearing of material on the shear plane, which results in less reactive forces on a cutting tool.

Finally, it is observed that grains in the CT chip are highly elongated as compared to that of in HFT. These elongated and small width grains, makes the chip harder which exerts significant abrading forces on the cutting tool. However, during the HFT, no elongation appears in the grain. It shows recovery taking place during machining process. Thus, chips appear completely strain relieved which also means less hardened chips obtained during HFT. These chips exert less reactive forces on the cutting tool.

In summary, The HFT can be used as a novel manufacturing technology to improve the machinability of Ti-6Al-4V or any hard-to-machine alloys. FE Modeling of the HFT Process shows that reduction in shear friction constant gives lower cutting forces in HFT than those in CT. The HFT generates matte surface finish with lesser average surface roughness (Ra) than CT. However, CT produces glossy surface finish. Grains that are less deformed and of small width produced during HFT process lead to a reduced hardened surface layer over that of in CT.
The HFT produces thin and crack associated chips. However, CT produces thick and uneven chips. A reduction in cutting temperature generated during HFT leads to a less thermal softening. Hence, an increase in chip length per softening has been observed during HFT over CT. A reduction in chip thickness for HFT chips, leads to a reduction in chip compression factor over the CT chips. An increased pitch length for HFT chips shows an increased chip length per softening over the CT chips. The higher shear angle for HFT chips, leads to a reduction in cutting forces over that of in CT. A reduced included angle and crack angle for the chips obtained from HFT leads to a less plastic deformation prior to fracture. The shear band formation is not observed for HFT chips, during HFT. The formation of crack at the shear plane at HFT chips shows less reactive forces on the cutting tool. HFT chips shows strain relieving of grains during chip formation. However, elongated grains in CT chips show hardening of grains during chip formation.

It is evident from the foregoing discussion that the invention has a number of embodiments. These are:

1. An apparatus for machining including turning, drilling and tapping of difficult-to-cut alloys for example titanium alloys, said apparatus comprising a work piece holder for holding a work piece made of hard-to-machine alloy, a horn made of said alloy on which a cutting tool is mounted, a tool assembly holder, a concentrator, a piezoelectric
An apparatus as described in embodiment 1, characterised in that said alloy is Titanium.

3. An apparatus as described in embodiments 1 and 2, characterised in that said machining process is turning.

4. An apparatus as described in embodiments 1 to 3, characterised in that said holder is a cylindrical rod.

5. An apparatus as described in embodiments 1 to 4, characterised in that said work piece moved with a constant velocity in the range of 150 to 330 mm/s.

6. An apparatus as described in embodiments 1 to 5, characterised in that said high frequency vibrations have a frequency in the range of 15 to 25 kHz and amplitude in the range of 10 to 40 µπη.

7. A method of machining including turning, drilling and tapping of work pieces made from hard-to-machine alloys using a turning apparatus as described in embodiments 1 to 6, characterized in that said method incorporates the step of making an intermittent contact between the cutting tool and the surface of said work piece with the help of high frequency vibrations.

8. A method as described in embodiment 7, characterised in that said machining process is turning.
9. A method of turning work pieces as described in embodiments 7 and 8, characterised in that said turning apparatus is operated as follows:

- holding securely said work piece in said work piece holder
- rotating said work piece about its central axis,
- transferring electric signal from said generator to said piezoelectric transducer
- using piezoelectric transducer, converting said electric signal into High Frequency mechanical vibrations
- amplifying said mechanical vibrations using the concentrator
- transferring said amplified vibrations via the horn to the cutting tool insert
- holding in a tool holder the entire vibrating assembly comprising said insert (tool), said horn, said concentrator, said piezoelectric transducer, and said electric signal generator
- bringing said tool holder, by moving it in the direction perpendicular to the plane of rotation of said work piece, maintaining it in contact with said work piece
- maintaining the forward movement of said tool holder while maintaining said vibration of the cutting insert in a direction parallel to said axis of rotation of said work piece, thereby maintaining an intermittent contact between said work piece and said tool insert.
10. A method of turning work pieces as described in embodiments 7, 8 and 9, characterised in that said work piece moved with a constant velocity in the range of 150 to of 330 mm/s.

11. A method of turning work pieces as described in embodiments 7 to 10, characterised in that said high frequency vibrations have a frequency in the range of 15 to 25 kHz and amplitude in the range of 10 to 40 μm.

12. A Method of turning a workpiece as described in embodiments 7 to 10, characterised in that the high frequency vibrations produce shifted chip segments with matte finish on the machined surface.

While the above description contains much specificity, these should not be construed as limitation in the scope of the invention, but rather as an exemplification of the preferred embodiments thereof. It must be realized that modifications and variations are possible based on the disclosure given above without departing from the spirit and scope of the invention. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their legal equivalents.
Claims:

1. An apparatus for machining including turning, drilling and tapping of difficult-to-cut alloys for example titanium alloys, said apparatus comprising a work piece holder for holding a work piece made of hard-to-machine alloy, a horn made of said alloy on which a cutting tool is mounted, a tool assembly holder, a concentrator, a piezoelectric transducer, an electric signal generator, characterized in that high frequency vibrations are imposed on the movement of the cutting tool.

2. An apparatus as claimed in claim 1, characterised in that said alloy is Titanium.

3. An apparatus as claimed in claims 1 and 2, characterised in that said machining process is turning.

4. An apparatus as claimed in claims 1 to 3, characterised in that said holder is a cylindrical rod.

5. An apparatus as claimed in claims 1 to 4, characterised in that said work piece moved with a constant velocity in the range of 150 to of 330 mm/s.

6. An apparatus as claimed in claims 1 to 5, characterised in that said high frequency vibrations have a frequency in the range of 15 to 25 kHz and amplitude in the range of 10 to 40 µm.

7. A method of machining including turning, drilling and tapping of work pieces made from hard-to-machine alloys using a turning apparatus as claimed in claims 1 to 6, characterized in that said method incorporates the
step of making an intermittent contact between the cutting tool and the
surface of said work piece with the help of high frequency vibrations.

8. A method as claimed in claim 7, characterised in that said machining
process is turning.

9. A method of turning work pieces as claimed in claim 7 and 8,
characterised in that said turning apparatus is operated as follows:
- holding securely said work piece in said work piece holder
- rotating said work piece about its central axis,
- transferring electric signal from said generator to said piezoelectric
  transducer
- using piezoelectric transducer, converting said electric signal into
  High Frequency mechanical vibrations
- amplifying said mechanical vibrations using the concentrator
- transferring said amplified vibrations via the horn to the cutting tool
  insert
- holding in a tool holder the entire vibrating assembly comprising said
  insert (tool), said horn, said concentrator, said piezoelectric
  transducer, and said electric signal generator
- bringing said tool holder, by moving it in the direction perpendicular
to the plane of rotation of said work piece, maintaining it in contact
with said work piece
- maintaining the forward movement of said tool holder while maintaining said vibration of the cutting insert in a direction parallel to said axis of rotation of said work piece, thereby maintaining an intermittent contact between said work piece and said tool insert.

10. A method of turning work pieces as claimed in claims 7, 8 and 9, characterised in that said work piece moved with a constant velocity in the range of 150 to of 330 mm/s.

11. A method of turning work pieces as claimed in claims 7 to 10, characterised in that said high frequency vibrations have a frequency in the range of 15 to 25 kHz and amplitude in the range of 10 to 40 \( \mu \text{m} \).

12. A Method of turning a workpiece as claimed in claims 7 to 11, characterised in that the high frequency vibrations produce shifted chip segments with matte finish on the machined surface.
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. B23B29/12 B23B1/00 B23P25/00

**ADD.**

According to International Patent Classification (IPC) or to both national classification and IPC.

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

B23B B23P B06B

 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal , WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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[| X | Further documents are listed in the continuation of Box C. | X | See patent family annex. |

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Date of the actual completion of the international search

3 December 2015

Date of mailing of the international search report

11/01/2016

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