Recent advances in ultrasonic assisted turning: A step towards sustainability

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Abstract: In order to meet the stringent environmental obligations, the research in the recent past has been focused on adopting sustainable techniques in industrial sector. Ultrasonic assisted turning (UAT) process has been developed in this regard to machine difficult to cut materials like alloys of nickel, titanium and composite materials. The present paper presents a thorough literature review to highlight the advantages in terms of low cutting forces and stress levels developed in UAT as compared to conventional turning process. In UAT, the cutting tool is imparted ultrasonic vibrations and hence an intermittent cutting mechanism is dominant. A decreased tool wear accompanied with compressive residual stresses in the machined part has made UAT a viable alternative to machine the advanced materials. The chip analysis has been shown to indicate that there occurs less plastic deformation in the material during UAT. The main objective of the present review article is to highlight advantages of UAT and to encourage the same by discussing a way forward to make it cost effective and environment friendly by reducing the carbon footprints of machining.

Subjects: Clean Tech; Manufacturing Engineering; Sustainable Engineering & Manufacturing

Keywords: ultrasonic; turning; conventional; forces; environment; carbon footprints; sustainable; environmental sustainability engineering

1. Introduction

The machining of new materials used in aerospace, defense, aeronautical, medical and electronic industry, possessing wear resistance, high strength at elevated temperature, resistance to chemical degradation create enormous challenges for the researchers. The main obstacle in the commercialization of these materials is their poor machinability. The excessive tool wear, difficulty in chip

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PUBLIC INTEREST STATEMENT

The environmental impact on machining is being extensively studied among the researchers. The carbon footprint of machining is reduced by adopting several sustainable techniques in manufacturing. Among the various new methodologies, ultrasonic assisted turning is widely used. The present research paper highlights the recent trends towards attaining sustainable manufacturing by adopting ultrasonic assisted turning. The future framework has also been highlighted by hybridizing the ultrasonic assisted turning to draw benefits of sustainable manufacturing.
formation, poor surface quality, high heat and/or cutting forces are the bottlenecks of conventional turning (CT). Moreover, the low thermal conductivity, high specific heat, and high strain hardening in conjunction with chemical reactivity with most of the cutting tool materials also result in extreme difficulty in machining such advanced engineering materials.

The turning of high strength alloys with the conventional process is generally characterized by low depth of cut and low feed rate which in turn affects the material removal rate (MRR). During machining operation of such alloys, Zhou and Hu (2015) reported high cutting forces on the tool significantly raises the stress, strain and temperature in the cutting zone, which influences the quality of the machined part. The functional performance of the component used in the high end industries is significantly affected by the properties of the surface generated by machining. Ahmed, Mitrofanov, Babitsky, and Silberschmidt (2006) found the tensile residual stresses accompanied with plastic deformation in the CT process, results in a premature failure and reduction in the life span of the component produced. Moreover, Maurotto, Muhammad, Roy, Babitsky, and Silberschmidt (2012) pointed out that the cutting tool suffers from abrasion wear on the rake face because of the presence of super hard carbide particles in the microstructure of Ni-based alloys and diffusion wear accompanied with built up edge (BUE) result in serious problems while CT of Ti-based alloys.

In order to alleviate the drawbacks of dry machining, Chetan, Ghosh, and Venkateswara Rao (2015) and Sharma and Pandey (2016) reported several sustainable techniques in manufacturing have been adopted for cleaner production. In this regard, cutting tool based technique is a recent trend adopted by several researchers which provides immense benefits for environmental friendly machining. Among the several sustainable manufacturing technologies, Xing, Deng, and Zhao (2014) presented significant improvements while dry machining using textured cutting tools. They reported nano and micro scale textures to not only to act as a storehouse of lubricant but also to reduce the frictional force between the chip and tool. In a similar approach, Xie, Luo, He, Liu, and Tan (2012) presented the use of textured cutting tools to machine difficult to cut materials like titanium. They used the micro-grinding process for texture creation and reported reduction in the temperature while machining due to the aerodynamic lubrication. In order to further enhance the effectiveness of self-lubricating tools, Wu, Deng, Su, Luo, and Xia (2014) used pulsating heat pipe to extract heat from the machining zone at a faster pace. Though, the above discussed cutting tool based techniques are effective in force and temperature reduction, but Chetan et al. (2015) presented some drawbacks of textured cutting tool like high cost in terms of pattern production. The present review article presents a novel ultrasonic assisted turning (UAT) process which can enhance the MRR, prevent excessive plastic deformation, achieve ductile mode of cutting and induce the compressive residual stresses in the work part.

Brehl and Dow (2008) reported that UAT involves high frequency and low amplitude motion imparted to the tool against the rotating work piece. This results in a periodic separation between the tool and work material. The tool can be given a motion in one direction (1D UAT; Figure 1(a)), or in a combination of two directions (2D UAT; Figure 1(b)) to have a linear or elliptical motion of the cutting tool work piece in (a) 1D UAM (Patil et al., 2014); (b) 2D UAM (Nath, Rahman, & Neo, 2009).
edge. Tabatabaei, Behbahani, and Mirian (2013) have found that there occurs a reduction in the chatter produced during machining with ultrasonic assistance. However, Khajehzadeh and Razfar (2015) reported that there occurs an increase in the cutting tool life, reduction in the cutting forces and better surface finish by providing ultrasonic assistance to the cutting tool.

The mechanism of UAT can be divided into four stages during one cycle of vibration of cutting tool as shown in Figure 2. Cakir, Gurgen, Sofuoglu, Celik, and Kushan (2015) in their findings showed that in stage 1, the cutting tool approaches the chip; while in stage 2 the cutting tool comes in the contact with the chip. The tool is in full contact with the chip and starts penetrating into the work piece in the stage 3. When the highest level of stress is reached, it marks the maximum penetration depth attained by cutting tool. This stage of UAT is similar to CT process as the tool is in full contact with the chip. In the last stage, the direction of the cutting tool is reversed and there occurs an unloading of tool from the work piece and this stage of UAT results in a reduction of the stress level attained in the work piece.

The above explained mechanism indicates that the stress variation in UAT is quasistatic in nature, ranging from maximum in stage 3 to minimum values in the other stages. This variation in the stress level results in a reduction in the average cutting forces between the tool and work piece. However, Maurotto, Muhammad, Roy, and Silberschmidt (2010) found that as the cutting speed increases the possibility of tool separation from chip decreases and results in continuous cutting even under the application of ultrasonic vibrations given to the tool. It has been found by various researchers that only for a particular set of vibration parameters (frequency and amplitude) and cutting parameters (cutting speed, feed and depth of cut) there results a tool-workpiece separation.
| Author                      | Work material          | Cutting tool              | Cutting parameters (cutting speed($V$); RPM($N$); depth of cut($d$); feed rate($f_r$))                                                                 | Vibration parameters (frequency($f$); amplitude($a$)) | Cutting force (in comparison to conventional turning) | Temperature measurement (in comparison to conventional turning) | Other output responses                                                                 |
|-----------------------------|------------------------|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Maurotto, Muhamad, et al.   | Ti 15-3-3 and Ni-625   | SECO DNMG 150608 MF1 CP500 | $V = 10$ m/min; $d = 0.100$ μm; $f_r = 0.1$ mm/rev                                                                                         |                                                      | 70% reduction                                       |                                                                                                                   | 2–3 times improvement in material removal rate                                      |
| Ahmed et al. (2006)         | Inconel718             | Tungsten carbide insert(DCMT 11T304) | $N = 40$ rpm; $d = 0.1$ mm; $f_r = 0.03$ mm/rev                                                                                             |                                                      |                                                      |                                                                                                                   | Hardness of the hardened layer in UAT was 60% less                                             |
| Muhamad et al. (2013)       | Ti15V-3Cr3Al3Sn (β-Ti alloy) | PVD coated TiAlN (DNMG150608 By SECO) | $V = 10$ m/min; $d = 0.1–0.5$ mm; $f_r = 0.1$ mm/rev                                                                                       | $f = 20kHz$; $a = 8$ μm.                          | 45–70% reduction                                      | Temp. was found to increase                                                                                         | 3D thermo mechanically coupled FEM model was developed                               |
| Babitsky, Mitrofanov, and Silberschmidt (2004b) | Inconel718 | V = 170/min; $d = 0.8$ mm; $f_r = 0.05$ mm/rev | $f = 20kHz$; $a = 15$ μm                                                                                                                   |                                                      | 15% higher                                           | Improvement in roughness by 50%                                                                                     | Less influence on microstructure of the machined part                                |
| Xiao, Karube, Soutome, and Sato (2002) | S45C | MF10 (Mitsubishi) | $V = 58$ m/min; $d = 0.05$mm; $f_r = 0.051$ mm/rev                                                                                           | $f = 20kHz$; $a = 15$ μm                          |                                                      |                                                                                                                   | Chatter was found to decrease in UAT with an increase in the rake angle                 |
| Patil et al. (2014)         | Ti6Al4V                 | Kennametal (DNMG-150608KC9225) | $V = 10–300$ m/min; $d = 0.1$ mm; $f_r = 0.1$ mm/rev                                                                                      | $f = 20kHz$; $a = 20$ μm                           | 40–45% reduction                                      | 48% reduction                                                                                                    | 40% reduction in the surface roughness                                                |
| Lin and Zhong (2006)        | A355/ SiC/20p           | Single crystal diamond insert | $V = 1.5–3$ m/min; $d = 1–3$ μm; $f_r = 5–15$ μm/rev                                                                                        |                                                      |                                                    |                                                                                                                   | Less elongated chips were formed in UAT                                                   |
| Maurotto, Roy, Babitsky, and Silberschmidt (2012) | Ti 15-3-3 and Ni-625 | SECO DNMG 150608 MF1 CP500 | $f = 17.8kHz$; $a = 12$ μm                                                                                                                   |                                                      | 70–75% reduction in tangential force;71–78% reduction in the radial force                                       |                                                                                                                   | 200% increase in the MRR                                                                     |
| Maurotto et al. (2013)      | Ti 15-3-3-3 (β-Ti-alloy) | SECO DNMG 150608MF1 CP500 | $V = 10–70$ m/min; $d = 50–500$ μm; $f_r = 0.1$ mm/rev                                                                                     | $f = 17.9kHz$; $a = 10$ μm                        | 71–88% reduction in the radial cutting force            | 3 times more MRR                                                                                                  |                                                                                                                   |
| Ahmed et al. (2007)         | Inconel 718             | Sandwich coromant DCMT 11T304 | $V = 5–16$ m/min; $d = 0.1–0.3$ μm; $f_r = 0.03–0.1$ mm/rev                                                                               | $f = 20kHz$; $a = 26.4$ μm                        | 30% reduction in the cutting fluid with the cutting fluid                                              | ElectrolubeHDC400 cutting fluid was used                                                |                                                                                                                   |
| Chua et al. (1998)          | Optical plastic         | Single crystal diamond insert | $f = 20kHz$; $a = 26.4$ μm                                                                                                                   |                                                      |                                                    |                                                                                                                   | Surface roughness was less than 1 μm                                                       |

(Continued)
In order to have intermittent cutting Vivekananda, Arka, and Sahoo (2014) proposed $v_c > V$; should be maintained by selecting the parameters of vibration and rotational speed appropriately, where $v_c = 2\pi a f$; represents the critical cutting speed and $V = \pi D N$ represents the cutting speed of the work piece, where $a$ is the amplitude and $f$ is the frequency of vibration, $D$ represents the diameter and $N$ is the rotational speed of the work piece. Table 1 presents detailed information of the work reported in the field of 1D UAT. The following sections presents a thorough literature review in the field of cutting forces, cutting temperature, stress levels, tool wear, surface roughness and residual stresses developed in the work material and highlights a comparative analysis between UAT and CT process. The main questions highlighted in this review paper are as follows:

### Table 1. (Continued)

| Author                  | Work material                      | Cutting tool                      | Cutting parameters (cutting speed($V$); RPM($N$); depth of cut($d$); feed rate($f_r$)) | Vibration parameters (frequency($f$); amplitude($a$)) | Cutting force (in comparison to conventional turning) | Temperature measurement (in comparison to conventional turning) | Other output responses                      |
|-------------------------|------------------------------------|-----------------------------------|----------------------------------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|------------------------------------------------------------------------------------------|---------------------------------------------|
| Nath et al. (2008)      | Inconel718                          | CBN(BN250)                        | $V = 5–20$ m/min; $d = 0.10$ mm; $f_r = 0.025–0.1$ mm/rev                                | $f = 19$kHz; $a = 15$ μm                               | 15–25% reduction                                     | 75–85% increase in roughness                                                              | Tool wear was less than 12–25%             |
| Muhammad, Hussen, et al. (2014) | Ti6Al2Sn–4Zr6Mo ($\alpha + \beta$ Ti alloy) | Cemented carbide insert with coating of Ti–Al Nitride(CP500) | $V = 10–60$ m/min; $d = 0.2$ mm; $f_r = 0.1$ mm/rev                                    | $f = 20$kHz; $a = 10$ μm                               | 74% reduction                                       | 18% increase in temp. rise                                                                | 50% improvement in surface roughness      |
| Muhammad, Maurotto, et al. (2014) | Ti-15333 ($\beta$-alloy) | Cemented carbide insert           | $V = 10$ m/min; $d = 100–500$ μm; $f_r = 100$ μm/rev                                  | $f = 20$kHz; $a = 8$ μm                                 | 80–85% reduction in HUAT                            | Temp. increase by 50%                                                                    | 50% improvement in surface roughness      |
| Nath et al. (2007)      | Low alloy steel (DF2)               | CBN (Carbon Boron Nitride)        | $V = 50–90$ m/min; $d = 0.2$ mm; $f_r = 0.1$–0.2 mm/rev                                | $f = 19$kHz; $a = 15$ μm                               | 50% reduction                                       | Roughness was found to be less than 1 μm                                                  | Wear was found to be less                 |
| Nestler and Schubert (2014) | Aluminiun matrix composite (25% SiC) | CVD diamond tip insert            | $V = 25–100$ m/min; $d = 0.5$ mm; $f_r = 0.1$ mm/rev                                  | $f = 24$kHz; $a = 2–4.9$ μm                             | Residual stresses were found to increase with the vibrations in the radial direction    | Ultrasonic vibrations in the cutting direction were found to affect the surface roughness | Residual stresses were found to increase with the vibrations in the radial direction    |
(1) What are the benefits of ultrasonic assistance to the cutting insert for improving the machinability?
(2) Why the use of UAT is the most apt sustainable manufacturing technique for machining difficult to cut materials?
(3) What are the main paths for future research regarding UAT process?

In the following sections the answers to the above raised questions have been answered using a systematic review methodology as proposed by Denyer and Tranfield (2009).

2. Systematic review methodology
The aim of the present review paper is to cater the researchers, students and industrialists who focus on environmental aspects of machining and try to mitigate the adverse impacts of CT. The systematic review in this regard has been focused on the research questions as pointed earlier. The present methodology is based upon the Denyer and Tranfield (2009) that has been widely acclaimed methodology for presenting a systematic review. In this regard, Ceulemans, Molderez, and Van Liedekerke (2014) used the systematic review methodology for sustainability reporting in higher education and Schulze, Nehler, Ottersson, and Thollander (2015) presented a conceptual framework for energy management in industry. This methodology involves locating relevant existing studies, evaluating the contributions of the various researchers and to provide clear conclusions and further research that can be intended in the near future.

2.1. Locating studies
For locating the studies science direct, scopus and web of science have been used to select the peer reviewed papers based on two keywords i.e. 1D UAT and ultrasonic assisted machining. The selection of the keywords used in the electronic database search has been based on keeping the essence of the proposed research questions. Table 2 presents the paper available in different sources as per the formulated keywords.

| Table 2. Locating studies in different electronic databases |
|----------------------------------------------------------|
| Search strings in abstract, title and keywords           | Electronic database search |
|                                                        | Science direct | Web of science | Scopus |
| String 1: One dimensional ultrasonic assisted turning   | 218            | 88             | 118    |
| String 2: Ultrasonic assisted machining                 | 675            | 179            | 416    |
| Total                                                   | 893            | 269            | 534    |

| Table 3. Criterion for the inclusion and exclusion of the research articles |
|--------------------------------------------------------------------------|
| Criterion                  | Inclusion                                                                 |
| Publication type           | Peer reviewed Journal and conference articles                              |
| Research discipline        | Engineering                                                                |
| Time period                | 1984–2015                                                                 |
| Sector                     | Manufacturing industry in particular turning                                |
| Language                   | English                                                                    |
| Relevance                  | Articles related to the advancements in turning having one dimensional motion of the cutting tool |
|                           | Articles related to the ultrasonic assisted machining but not involving turning process in specific |

Books and periodicals
Irrelevant articles not related to the field of engineering
No relevant paper was found prior to 1982. The research article related to cryogenic treatment appeared in this year only
Milling, drilling, finishing, EDM
Any other language
2.2. Study selection and evaluation

It is performed in order to meet the transparency requirement as proposed by Denyer and Tranfield (2009). This step is based on the explicit selection criteria to find those academic journals which could address the research questions as proposed in Section 1. However, due care has been taken for reasons formulated for the exclusion part, so that the it’s not the quality of research rather all those peer reviewed articles are selected those answer the proposed research questions (refer Table 3).

Based on the manual review work related to the title and abstract reading the papers not pertaining to the turning process in specific were removed from the database. This left with 95 articles related to turning and sustainable manufacturing techniques. This has been based on selecting only those peer reviewed articles which had turning in their keywords or title (using Jabref).

3. Cutting forces

The effectiveness of the cutting process is governed by cutting forces, which are primarily affected by the cutting conditions (velocity \( V \), feed \( f \) and depth of cut \( d \)), cutting tool geometry (rake angle) and properties of the work material. Muhammad, Maurutto, Roy, and Silberschmidt (2011) proposed that any method for the reduction of the cutting force would result in an extension of the tool life and a better surface finish of the machined part. The following section highlights the benefits of 1D UAT in the reduction of the cutting forces.

Patil, Joshi, and Tewari (2012) reported a reduction of 44 and 50% in the cutting and thrust force respectively during UAT of Ti6Al4V. The simulation studies found that for constant amplitude and cutting speed, an increase in the frequency of vibration decreased the forces. However, Ahmed, Mitrofanov, Babitsky, and Silberschmidt (2007) found that for a constant frequency, an increase in the amplitude of vibration decreased the forces up to a particular value after which an increase in the amplitude was found to have a negligible effect on force reduction. This can be accounted for the reason that with an increase in the amplitude and frequency, there occurs an increase in the critical cutting speed. This helps to decrease the Tool Workpiece Contact Ratio (TWCR) as proposed by the following author.

Nath and Rahman (2008) introduced the concept of ‘TWCR’ for the reduction of cutting forces in UAT. TWCR has been defined as the ratio of the time for which the tool is in contact with the workpiece to the total time of vibration of one cycle i.e. \( TWCR = \frac{1}{T} \) (refer Figure 3).

They reported that an increase in the frequency and vibration amplitude resulted in a reduction of TWCR, which increased the non-contact time of the tool and hence an intermittent cutting mechanism. The author reported that for machining Inconel 718, a proper selection of frequency, amplitude and cutting speed which decreased the TWCR, resulted in 12–25% reduction in the cutting forces.

![Figure 3. Cutting state in UAT process.](image-url)
compared to the CT process. However, Maurotto, Muhammad, et al. (2012) found a reduction of 70–75% in the tangential and 71–78% in the radial force while machining Ti 15-3-3-3 and Ni-625. Such a large reduction in the cutting forces while machining the advanced material was accounted because of the ultrasonic softening found in the Ti based alloys. Also, for the same vibration and cutting conditions, the force reduction in Ni based alloy was found to be 50% higher than that found in the Ti based alloy. This was because of the more strain hardening effect found in the former material.

In another research attempt, Ahmed et al. (2007) found that in 1D UAT the ultrasonic vibrations in the tangential direction were more beneficial for force reduction as compared to vibrations given in the feed direction. Moreover, the authors reported a reduction in the average cutting forces with an increase in the amplitude and an increase in the frequency of vibration while machining Inconel 718 by UAT. Such a reduction in the forces can be explained because of an increase in the ultrasonic vibration velocity imparted to the cutting tool, which is directly proportional to the amplitude and frequency of vibration as reasoned earlier.

Muhammad, Roy, and Silberschmidt (2013) reported a reduction in the cutting forces during UAT because of the periodic separation between the tool and work piece in one cycle of ultrasonic vibration. Moreover, the simulation studies found the force reduction to be highly dependent upon the tool edge radius. A decrease in the tool radius from 25 to 0 μm resulted in a reduction of 15, 69 and 68% in the $F_x$, $F_y$, $F_z$ components of the cutting forces while machining Ti15V3Cr3Al3Sn by UAT process.

Maurotto, Muhammad, Roy, and Silberschmidt (2013) pointed that an increase in the cutting forces with an increase in depth of cut (Figure 4(a)) and cutting speed (Figure 4(b)). The forces in UAT process were found to be more sensitive to the cutting speed as compared to the CT. This can be because in UAT the force reduction is characterized by the critical cutting speed. In their work, the critical cutting velocity, which is dependent upon the amplitude and frequency of the vibration, was 75.32 m/min. Thus, an increase in the cutting velocity will decrease the tool separation and hence a decrease in the force reduction.

Attempts have also been made to decrease the shear strength and strain hardening rate of the advanced alloys using thermal softening. In this regard, Muhammad, Maurotto, Demiral, and Roy (2014) developed a novel, HUAT (Hot Ultrasonic Assisted Turning) process which resulted in 80–85% decrease in the cutting forces while machining Ti 15-3-3-3. The thermal softening decreased the yield strength of the advanced material, which resulted in an ease in the cutting process. Also, the superimposition of the ultrasonic vibrations helped to attain such a large force reduction.

Thus it can be seen that UAT and its recently developed variant HUAT are found to be effective in the force reduction, because of the intermittent cutting. However, force reduction is found to be highly dependent upon an appropriate selection of the cutting parameters and vibration parameters. For ultrasonic horn of standard frequency, the cutting speed, diameter of the work piece play a significant role in making UAT a viable alternative for force reduction.
4. Stress levels
The high value of normal stresses during machining can result in seizure on the rake face. The value of stress on rake face can be 5–10 times higher than on the tool edge. Thus, the study of stress variation is important for analyzing the machining operation. Patil, Joshi, Tewari, and Joshi (2014) reported a transient state of stress in UAT of Inconel 718. It has been found that in stage 3 (when tool is in full contact with the chip), the state of stress is similar to the CT process. However, Mitrofanov, Ahmed, Babitsky, and Silberschmidt (2005) found the state of stress in the other stages remained fairly quasistatic. Moreover, an increase in the cutting speed increased stress levels in UAT, because in such a case the TWCR increased.

The difference between the percentage of effective stress attained in CT and UAT decreased with an increase in the cutting speed. This may be due to the reason that as the cutting speed approaches the critical speed, UAT tries to follow CT process, which results in more contact between tool and chip and hence a higher stress levels are attained.

In a similar approach, Muhammad, Maurotto, et al. (2014) reported the stress distribution in CT to be concentrated in the primary and secondary zones of the cutting. However, in UAT and HUAT the stress levels were found to be transient in nature. Such a trend decreased the average level of the Von-Misses stress in the cutting region in one complete cycle of HUAT.

Thus, it can be seen that the ultrasonic assistance to the cutting tool decreased the average stress attained in the machining zone. Such a decrease helped to improve the tool life by decelerating the tool wear and thus results in more stable cutting mechanism. This has been explained in the following sections by highlighting a comparative analysis between CT and UAT machining region.

5. Cutting temperature
The poor thermal conductivity, high chemical affinity and abrasivity of advanced alloys result in enormous challenges while machining such materials by CT process. However, an increase in the cutting temperature can result in the thermal softening (reduction in the yield stress and other mechanical properties) and therefore result in an ease in material removal. But, an excessive heat may have an adverse effect on the tool life. Though Mitrofanov et al. (2005) have recommended the use of cutting fluid during turning in order to reduce the temperature in the process zone; but, because of the environmental considerations dry machining has been preferred in UAT.

Patil et al. (2014) reported a reduction in the maximum temperature attained by the cutting tool in UAT. It was found that the temperature in process zone was dependent upon the cutting speed (Figure 5). At low cutting speed (10 m/s), the temperature in UAT process was higher than the CT process. This may be because at such a low speed, the critical velocity \( v_c \) was much higher than the feed velocity, which resulted in more vibro-impacts and hence a rise in temperature as compared to CT process.

Figure 5. Variation of machining temperature with cutting speed (Patil et al., 2014).
Mitrofanov, Babitsky, and Silberschmidt (2004) performed the simulation of UAT and CT process and reported 12% higher cutting temperature in CT process. The authors explained that the intermittent mechanism of UAT resulted in only 40% of the contact between the tool and work piece in one cycle of vibration, which caused a temperature reduction. The less contact led to a reduction in the thermal conduction between the tool and chip and an increase in the convective heat transfer coefficient. These factors were found to be the predominant reasons for the temperature reduction in UAT.

However, contradictory to the work reported by previous researchers, Babitsky, Kalashnikov, and Molodtsov (2004a) found a temperature rise in the chip and the cutting tip by 15% during UAT. They accounted additional energy supplied by the vibration to result in high strain rate in the machining zone which was found to be responsible for the temperature rise. Khajehzadeh, Akhlaghi, and Razfar (2014) reported temperature distribution in the machining zone while turning aerospace aluminium based alloy. The authors validated their experimental findings using finite element method. The time of separation between tool and work piece was found to be the main contributor in less temperature rise in UAT.

In a yet another research attempt, Maurotto and Roy (2014) found an increase in temperature with an increase in the depth of cut; whereas, Muhammad, Maurotto, et al. (2014) reported an increase in the cutting temperature with an increase in the cutting speed. The temperature in the process zone for CT and UAT while machining Ti-676-0.9La was found to be 100–150°C higher when compared to the machining of Ti-6246. Thus, the higher temperature found by the addition of rare earth metals in the Ti based alloy helped in pulverization of the chips during UAT and hence resulted in the formation of discontinuous chips while machining.

Overcash and Cuttino (2009) presented in process modeling of temperature distribution for the tool vibrating with ultrasonic frequency. The simulation studies revealed an increase in the process temperature with an increase in the cutting speed. However, vibration amplitude and frequency were found to reduce the diffusion wear and cutting temperature due to the intermittent cutting mechanism of UAT.

Moreover, Muhammad, Maurotto, et al. (2014) utilized the concept of thermal softening to reduce the cutting forces in HUAT. The subsurface deformation and microstructural changes of the machined part were found to be significantly affected by the maximum temperature in the process zone. However, a slight temperature reduction was observed during the retraction stage in HUAT.

Thus, the literature reveals a contradiction among various researchers regarding temperature distribution in the primary and secondary cutting zone in UAT. The primary reason for the increase of temperature in the metal cutting is due to the plastic deformation and friction between the tool and work piece. In UAT, the friction is found to decrease because of the intermittent cutting. Therefore, the possible reason for the increase in the temperature may be due to the additional energy supplied to the tool in the form of ultrasonic vibrations.

6. Surface roughness
The poor thermal conductivity of advanced materials result in a high temperature in the process zone, which affects the tool wear and hence the surface finish. Wang and Zhao (1987) were the pioneers in studying the surface roughness by imparting ultrasonic motion to the cutting tool. The poor surface finish of the machined part results in various post finishing operations, which ultimately enhances the manufacturing cost of the product. Moreover, surface quality is an important parameter which is directly related to the fatigue life of the component. Several attempts of UAT have reported an improvement in the surface finish of the product as compared to the CT process.
Maurotto and Roy (2014) reported a twofold improvement in the roughness value of Inconel 718 and Ti 15-3-3-3 by UAT in comparison to the CT process. The authors demonstrated the capability of UAT in attaining better surface finish by reducing the cutting forces up to 50% while machining intractable alloys. A reduction in the chatter and a stable cutting mechanism were found to play a predominant factor in attaining 0.505 μm $R_a$ while machining Inconel 718 during UAT.

Muhammad, Hussain, et al. (2014) reported 50% improvement in the $R_a$ value of ($\alpha + \beta$) Ti based alloys. The addition of La particles in the microstructure of Ti alloy was found to be beneficial in attaining better surface finish for both CT and UAT process. This can be accounted for the reason that the formation of discontinuous chips resulted in the attainment of better surface finish. In an another research attempt, Nath, Rahman, and Andrew (2007) found that a low feed rate helped in attaining better surface finish. The continuous contact between the tool and workpiece (during CT) resulted in the formation of BUEs which deteriorated the surface finish. However, the absence of BUE formation during UAT, helped to attain a better surface finish.

Gao, Zhao, Jiao, and Liu (2002) reported that the tool tip should be located lower than the rotating center of the work piece by three times the amplitude of vibration in order to had less ripples on the machined part. Moreover, the authors found that UAT process follow the same pattern in the surface roughness variation with the cutting parameters (refer Figure 6) as followed in the CT process. However, the surface roughness of the order of 30% less was found in the machined part by ultrasonic assistance to the cutting tool.

Chua, Chou, and Wong (1998) reported that an extremely low cutting velocity helped to attain better surface finish. At low cutting speed (below 1/10th of the critical cutting velocity), the formation of long, thin and continuous chips ensured the ductile mode of cutting which helped to attain surface roughness of the order of 0.38 μm while machining optical plastic polymethylmethacrylate (PMMA) during UAT process.

However, Nestler and Schubert (2014) found that the ultrasonic vibration in the cutting direction had no influence on the surface roughness. The authors reported that the ultrasonic assistance given to tool in radial direction was found to increase the surface roughness with an increase in the amplitude of vibration both in axial and circumferential direction.

In an another research attempt, Lin and Zhong (2006) studied the effects of ultrasonic and cutting parameters on the roughness value. A proper selection of cutting speed, feed rate and amplitude of vibration was found to significantly affect the surface roughness of the machined part. The authors reported high amplitude (3.7 μm) to improve the surface roughness by 15% than by the machining done with amplitude of 2.2 μm (Figure 7). This can be accounted for the reason of the ironing effect found in the ultrasonic machining.

Patil et al. (2014) related the improvement in roughness with TWCR. In CT, 100% TWCR deteriorated $R_a$ because of higher cutting forces and cutting instability. But in UAT, as TWCR decreased, resulting in force reduction, an improvement in the $R_a$ of machined part was observed (Figure 8). However, there occurs an optimum cutting velocity which provided the best surface finish for a particular set
of parameters. The authors reported that at a cutting velocity of 20 m/min, 40% improvement in the surface finish can be achieved in UAT of Ti6Al4V. However, beyond 20 m/min, the average surface roughness was found to increase. This may be because of the critical cutting velocity beyond this point attain such a speed that 100% TWCR occurs. This in turn reduces the ironing effect.

Thus, various research attempts had shown that UAT can significantly affect the surface roughness of the machined part. Ma, Shamoto, Moriwaki, Zhang, and Wang (2005) have reported the suppression of burrs while providing ultrasonic motion to the cutting tool. This can be reasoned because of the ironing effect which makes the tool transverse on the work piece several time in one cycle of vibration. However, a proper selection of cutting parameters and a proper location of the cutting tool with respect to the work piece play a significant role in producing less ripples during UAT.

7. Chip morphology
The chip formation affect the machining dynamics and its study is important for tool wear and tool life. It provides information of the stress distribution on the shear plane and the properties of material during the deformation process. Any method that can change the chip morphology can help to control the cutting forces and hence the machinability of the super alloys.

Patil et al. (2014) analyzed the effect of UAT on chip formation by studying the chips in detail as shown in Figure 9.

Figure 7. Effect of vibration and cutting condition on roughness for aluminium based composite material (Lin & Zhong, 2006).

Figure 8. Surface roughness variation with cutting speed (Patil et al., 2014).

Figure 8. Effect of vibration and cutting condition on roughness for aluminium based composite material (Lin & Zhong, 2006).
The analysis of chip formed during UAT showed less cutting forces with minimum plastic deformation while machining Ti based alloy. It was found that a continuous contact between the tool and work piece during CT resulted in the formation of thicker and continuous chips. But, because of the intermittent cutting in UAT, the chips formed were thinner and discontinuous. The continuous chips in CT process resulted in more abrading forces on the cutting tool. However, the chips formed in UAT produced less reactive forces on the tool rake face.

Muhammad, Maurotto, et al. (2014) studied the addition of lanthanum (La) particles in Ti-6246 (Figure 10), which resulted in less adhesion because of high temperature in the shear bands that melt the metallic La particles. The addition of rare earth metals, helped to create smaller and discontinuous chips, which prevented the entangling of the chip around the tool. The smaller and discontinuous chip resulted in less abrading forces on the tool rake face and hence improved the tool life.
Though the addition of La resulted in the formation of short chips in CT and UAT process; but the superimposition of the vibro-impact phenomenon of UAT process, resulted in shorter chips in the modified Ti based alloy as compared to the CT process (refer Figure 10(c) and (d)).

Moreover, the cutting parameters have been found to affect the chip compression ratio ($\lambda$), defined as Equation (1):

$$\lambda = \frac{h_{\text{max}} + h_{\text{min}}}{2d_c}$$  \hspace{1cm} (1)

where $d_c$ is the chip thickness, $h_{\text{max}}$ and $h_{\text{min}}$ are the maximum and minimum heights of the chip segment respectively (refer Figure 11).

Chip compression ratio indicates the state of plastic deformation during machining. The objective of machining is to have material cutting with minimum plastic deformation. Patil et al. (2014) reported chip compression ratio to be less in UAT as compared to CT. However, the cutting speed was found to have a linear relationship with the chip compression factor. From Figure 12, it is clear that lower cutting velocity resulted in less plastic deformation. The chip analysis showed that the shear angle along the plane of cutting is more in UAT. An increase in the shear angle was found to be responsible for the reduction in the cutting forces while machining Ti based alloy (Figure 13).

Contradictory to the work reported by earlier reported researchers, Nath and Rahman (2008) and Nategh and Eng (2009) found the formation of long, thin and smooth chips in UAT while machining St 1.991 and Inconel 718 respectively. The formation of thick and cracked chips significantly affected...
the tool life, by generating more abrading forces on the cutting tool. The research attempts on UAT showed that the newly developed process is highly capable of generating thin and discontinuous chips which enhances the tool life and a decreased tool wear as compared to the CT process.

8. Tool wear
Tool wear is a time dependent process. The cutting conditions, cutting tool geometry and properties of the work material are found to significantly affect the tool wear. It is therefore, an important parameter which has been related to the tool life. The following section provides a literature review regarding the tool wear, tool wear rate and tool life in UAT process.

Nath et al. (2007) reported a high tool wear in CT process. However, UAT was found to have an insignificant wear rate for an increase in feed and cutting speed (Figure 14). It was found that the abrasive wear rate was higher than any other wear mechanism. The continuous friction between the tool and work piece interface resulted in more abrasive wear in the CT process. However, the intermittent cutting mechanism of UAT allowed the tool to had aerodynamic lubrication for reducing the cutting temperature and hence less tool wear was observed. Moreover, the tool wear acceleration was found to be far less in UAT but, the wear rate of the tool in CT process showed a steep rise with the machining time.

Nath and Rahman (2008) reported the pattern for flank wear while machining Inconel 718. The authors reported formation of built-up-edge in CT process to leave the chip debris on flank and rake face, resulting in an increase of cutting forces and hence more tool wear. However, small amount of BUE and aerodynamic lubrication in UAT increased the tool life by reducing the tool wear. An increase of 7–8 times in the tool life of CBN inserts was found while machining Inconel 718 by UAT as compared to the CT process.
Weber, Herberger, and Pilz (1984) reported an increase of 20 times in the tool life of carbide cutting tool by providing ultrasonic vibration in the tangential and radial direction as compared to the CT process. The authors related the timely removal of the ceramic dust from the cutting zone while machining glass ceramics to be the predominant factor for less abrasive contact and hence lesser tool wear.

Thus, the cutting conditions significantly affect the tool wear. Though several studies have reported an increase in the tool life, but this contradicts the reporting of high temperature in the cutting zone during UAT.

9. Residual stresses
Surface integrity has been widely accepted as a measure of the quality of machined surface. In a turned machine part, the fatigue resistance is affected by the surface finish, phase transformation, cold working and residual stresses. However, residual stresses are a dominant factor affecting the fatigue resistance of a component. The residual stress depth, sign and magnitude are dependent upon the cutting velocity, tool pressure, feed, cooling and tool geometry. In most of the machining operations, surface residual stresses are tensile; however subsurface residual stresses are of compressive nature. The occurrence of compressive residual stresses results in an increase in the fatigue and corrosion life of the component.

Ahmed et al. (2006) measured the hardness and residual stresses using nano indentation test (Figure 15). It was found that the average hardness of the hardened layer in UAT is 60% less than that found in the CT machined part. Also, the hardness in the machined part of UAT was close to that of the un-machined part, which indicated that UAT was more delicate to the work piece being machined. Moreover, UAT lead to larger absolute value of the residual stresses in the machined part as compared to the CT process. The numerical modeling done using Johnson Cook Equation revealed that there occurs a higher value of the residual stresses of compressive nature in UAT machined part as compared to the CT process (refer Figure 15). The presence of compressive residual stresses can be accounted because of the vibro-impacts between the tool and workpiece during one cycle of vibration.
In another research attempt, Maurotto and Roy (2014) found an increase in the hardness of the surface layer with the variation in depth of cut (Figure 16). It was found that the hardness of the CT machined part varied from the bulk (un-machined part). Similar to the findings of Ahmed et al. (2006) the hardness in the UAT was found to remain fairly constant and near the bulk material hardness. This feature of UAT was found to be affected by the strain rate, metallurgical changes and residual stresses. Since in UAT the strain rate is higher, the hardness should have been more but Figure 16 showed the reverse phenomenon. This indicated that the strain rate was not the only main factor affecting the hardness of the machined part. The author reported the formation of white layer and heat affected zone to be the possible reason for the decrease in the hardness, found in UAT.

Nestler and Schubert (2014) found ultrasonic vibrations in the radial direction to be more effective in generating compressive residual stresses in the machined part as compared to the vibrations given in the cutting direction. However, the ultrasonic vibration in the feed direction was found to have no effect on the residual stresses. This can be accounted for the reason that such a tool motion provided neither an additive mechanical load nor a reduction in the thermal load. From Figure 17 it can be seen that an increase in the amplitude resulted in more compressive residual stresses in UAT of aluminium matrix composite material.

Thus, the material used in high performance and light weight industries like composites, Ni and Ti based alloys can be more effectively used if the fatigue life of the machined components can be increased. The most favorable method of enhancing the fatigue life is by inducing compressive residual stresses. Various attempts have found that UAT is a viable alternative for enhancing the fatigue life of the machined part in comparison to the CT process.

10. Conclusions and future scope

Thus, it can be seen that most of the research work in UAT has been carried out under dry conditions. The use of different environmental friendly lubricants in conjunction with UAT can be studied in future for further force reduction. In order to enhance the efficacy of the process, mathematical models can be developed for understanding the process physics of 1D UAT. It has been reported by several researchers that high strain rate is developed in the process zone because of the vibro-impact of tool and workpiece. The simulation studies in 1D UAT can be carried out using various commercially available software to understand the residual stress variation in the work material.

Statistical models for determining the cutting forces and surface roughness to understand the interaction between process parameters can be developed. These models will present a process window for selecting optimum parameters while machining difficult to cut materials. The research can also be focused on developing empirical models for minimum energy utilization during 1D UAT.

The following conclusions can be drawn from the above literature review one dimensional UAT while machining difficult to cut materials:

![Figure 17. Amplitude effect on generation of residual stresses in UAT (Nestler & Schubert, 2014).](image-url)
(1) A decrease in the average cutting forces is observed in UAT for machining a range of difficult to cut materials. The force reduction has been found because of the intermittent cutting mechanism of UAT.

(2) A proper selection of the cutting and vibration parameters plays a significant role in having a periodic separation between the tool and work piece.

(3) For machining materials with poor thermal conductivity, the problem of tool wear in CT process can be effectively overcome by providing ultrasonic assistance to the cutting tool.

(4) The compressive residual stresses generated in the machined part are found to enhance the fatigue life of the component used in the aerospace industry.

(5) The analysis of the chip indicates the generation of less cutting forces with minimum plastic deformation of the work material while machining advanced materials with the ultrasonic assistance to the cutting tool.

It can be deduced from the literature review that significant research work has been carried out to study the influence of ultrasonic vibrations while machining hard-to-cut materials. However, in the near future research can be focused on analyzing the material response to ultrasonic processing. In order to further enhance the efficacy of the UAT, other sustainable manufacturing methods like use of Minimum Quantity Lubrication, cryogenic cooling, textured cutting insert can be coupled with UAT process. These advancements will not only help to yield better results but will also pave the road for environmental friendly machining.

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