A review on feasibility study of ultrasonic assisted machining on aircraft component manufacturing

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Abstract. Inconel 718 has been widely used in aerospace because of its excellent mechanical properties such as good corrosion resistance, strong creep resistance and high fatigue strength. However, these excellent properties also lead to heavy tool damage and high cutting force in the milling process. There is no reported investigation on ultrasonic assisted machining (UAM) of Inconel 718 parts. In this paper, UAM is proposed as the potential technique to reduce tool damage and the cutting force of Inconel 718 parts. This review paper provides an overview of UAM to investigate the relationship between the tool wear and the cutting force with ultrasonic vibration compared to without ultrasonic vibration assisted. Throughout the study, the UAM scopes are related to the tool life of coated carbide insert, the force generated during the cutting process and also the final surface finish of the workpiece by using various parameters during the machining activity.

1. Introduction
Superalloy has been highly used in extreme applications due to its good mechanical properties. 80% of the superalloy usage such as Inconel 718 and Titanium is in the aerospace industry. Gas turbine engine (shown in Figure 1) uses nickel alloys for approximately 45-50% of its material [1-2]. Due to superior properties such as good corrosion resistance, strong creep resistance and high fatigue strength, nickel-based alloys is preferred to be used for the rotating and static components in the hottest section of aero engines such as the blades and disks in high-pressure turbine and compressor [3]. Inconel 718 (53.3% Ni, 18.5% Fe, 4.98% Nb, 3.03% Mo) [4] is considered as one of the metals that is very difficult to cut. Throughout the years, machinability of Inconel 718 still is the challenge for many researchers to fulfill higher manufacturing efficiency nowadays. Due to increased demands, this leads to a great innovation of advanced machining process. Cutting force is the crucial variable applied as the tool wear indicator among the indirect on-line tool wear monitoring methods. Measurement and study of the relationship and correlation between the means of tool wear and the cutting force is important for the development of the effective process or tool condition strategy [5-7].
Chatter is defined as regenerative vibration when the width of the chip is too large in comparison to the dynamic structure in a particular spindle speed [9]. Regenerative vibration is generated as a result of interaction between the cutting force and structural dynamics of the machine [10], and is considered as a dominant type of chatter in milling operation. If the mechanism is properly applied, the advanced technology such as Ultrasonic Assisted Machining (UAM) can provide positive effects on vibration suspension [11]. A recent study implies that ultrasonic vibration on the milling tool holder decreases the measured cutting force by 62%, which is small enough that the tool does not measurably deflect, enabling it to mill the surface square. This cutting force reduction leads to various potential benefits. In addition to potential improvement in feed rate, tool life and accuracy, less cutting force also means reduced power consumption [12].

As Inconel 718 is hard to cut, UAM will help the tool life where the cutting tools tend to get worn out faster during its conventional milling machining. UAM has shown a positive impact for the hard material surface roughness on finishing such as diamond turning of stainless steel [13] and ceramics [14]. In this paper, a review on the feasibility of UAM is done through previous experimental research and their results compared to conventional milling (CM) process on the Inconel 718 superalloy.

2. Machining of Inconel 718

Inconel 718 is a nickel-based superalloy that exhibits desirable properties over wide temperature range and it is widely used in industry. However, its excellent mechanical properties such as good corrosion resistance, strong creep resistance and high fatigue strength [15] are compromised by shear strength, strong work hardening and high-temperature tensile strength that shorten the tool life and cause severe work-surface damage during CM [16]. To improve machinability of superalloys, ultrasonic vibration assisted technique has been employed in the milling [17], drilling [18], grinding [19] and turning [20] processes. Although this technique has been implemented, it still has not been carried out for Inconel 718 in milling process yet.

2.1. Traditional milling process

Traditional milling process is divided into two types: climb and conventional milling. Conventional milling has a significant benefit when machining hard materials such as cast iron or hot rolled steel. In contrast, performing a climb mill on hot-rolled steel can result in chipped cutting edges because of the hardness of that outer layer and the more aggressive way the tool engages the rough surface, causing more deflection and potentially heavier chips. Since the tool deflection with a conventional mill tends to be parallel to the tool, it engages the rough surface at a more forgiving rate. Comparison between both milling types on Inconel 718 has been done [21, 22]. Through the research, it has been found that the tool flank wear propagation in the up milling (conventional milling) operation is more rapid than that in the down milling operations (climb milling) as shown in Figure 2. On the other hand, the chip morphology is different in both operations, where the up-milling operation produces a segmented chip with typical saw-tooth shape and the down-milling operation produces a discontinuous serrated chip. In general, tool wear is increased with increasing cutting speed, feed rate and depth of cut (DOC).
The results of conventional milling on hard materials have led to the UAM technique, which could be the solution to some of the problems encountered by CM. During the CM of Inconel 718, it is found that the tool wear is increased as the DOC, feed rate and cutting speed are increased [21]. The results have shown that the tool flank wear rapidly occurred, thus affecting the tool performance, tool life and workpiece surface. Significant notch and pitting are the predominant failure modes that are located near the line of DOC. Since Inconel 718 is a super-heat-resisting alloy, the tool life is shorter during the interrupted than continuous cutting process since the built-up edge (BUE) is removed. This causes the coating film to flake on the cutting tool, particularly during the machining of high tensile strength [23, 24].

The cutting tool is the equipment that is used to remove a material layer by layer. At a certain time, through the contact between the cutting tool and the workpiece, flaking and chipping (tool wear) will occur due to the interrupting cutting force (e.g. major failure mode during end milling of Inconel 718 due to interrupted cutting force as illustrated in Figure 3). During the dry cutting of Inconel 718, the flank faces and rake from welding and adhesion of workpiece are dominant wear modes [25] while the predominant failure modes of cemented carbide tool insert is found on flank wear and microchipping that affects the tool's life and performance [26].

Figure 2: Discontinuous serrated chip during end milling [21]

Figure 3: Major failure mode during end milling of Inconel 718 due to interrupted cutting force [24]

Figure 4 shows the chipping that occurred on the rake face due to interrupted nature of the cutting process. During the cutting of Inconel 718 using band-saw, the dominant wear mode is the flank wear (shown in Figure 4(a)). It has also been found that adhesion of the workpiece material onto the worn flanks promotes the adhesive-type wear flank wear to be developed at the cutting edge due to abrasive action between the flank face and machined workpiece (as shown in Figure 4(b)).

Figure 4: Adhesion of the workpiece on the: (a) side face of tooth corner and (b) flank face [27]
Since Inconel 718 is difficult to cut, a lot of heat is generated while machining it at high speeds. During the investigation of Inconel 718 machining in high-speed, it is found that at high cutting speed, heavy notching of major tool failure occurred because the tool got worn-out faster [28]. Wear patterns observed at these cutting speeds are uniform along the nose radius with some traces of peeling coating. In the same investigation, very high amount of heat in the cutting zone is generated while burns marks are visible on the cutting tool. The heat is diverted into the cutting tool because of the poor thermal conductivity of Inconel 718 and this could be one of the major reasons that leads to tool wear.

The illustration for the effect of tool geometry on residual stresses in machining IN-718 is shown in Figure 5. The cutting edge geometry also produces a ploughing effect due to the honed radius (cutting edge radius) compared to the chamfered tools that are said to increase the compressive nature of the residual stresses [29]. Coelho et al. (2004) [30] have also studied the effects of the tool chamfer edge geometry on residual stress in turning process of Inconel 718.

![Figure 5: Effect of tool geometry on residual stresses in machining of Inconel 718 [30]](image)

It is a general fact that the forces are strong indicators of the cutting performance, which are related to tool wear, surface finish and specific cutting energy (e.g. the variation in cutting length at different depths of cut is shown in Figure 6). The wear in cutting edge and the gradual degradation are indicated by the force components that increase steadily through the increment of cut length. The cutting tool is relatively sharp at the beginning, hence produces lower cutting force [31]. The increased wear of the edge leads to a blunt edge with increased contact area between the edge and workpiece, thus produces higher cutting forces [27]. The forces then served as a good indicator of the degradation of the cutting edge throughout its life. Similar results have been observed during the machining of steels with HSS band saws [32, 33].

![Figure 6: The variation in cutting length at different depths of cut [31]](image)
Combination of adhesive and abrasive wear with degrees of plastic deformation is the mechanism of flank wear. The reduction in the machining efficiency and increases in force components are led by the increment of the edge cutting radius and the BUE that formed during machining. Even with the removal of BUE, the force components will still decrease periodically as the carbide tip geometry has been significantly altered due to the loss of edge material through chipping or welding with BUE. The chipping and fracture occur due to the formation of micro-cracks. The general trend of specific cutting energies with the length of cut is shown in Figure 6 and it continues to increase by the degradation and wear of the cutting edge [33].

In a machining operation, the critical objective is to have a good surface finish. Surface finish is an important criterion in machining process and selection of proper machining parameters is important to obtain good surface finish. The presented image in Figure 7 shows a damaged surface of Inconel 718 at $V = 150 \text{m/min}$, $f = 0.15 \text{mm/rev}$, DOC = 0.50 mm and dry condition. In Inconel 718 case, the lower surface roughness is rarely achieved through CM due to interrupted cutting force phenomenon that is affecting the machine performance like tool wear, cutting force and surface roughness (e.g. variation in surface roughness for different speeds is depicted in Figure 8). This condition is because, at high speed, there is a possibility that a surface flaw is wiped-out and there is also a presence of heat in the cutting tool [28].

One of the problematic issues during the machining this alloy is the white layer. The requirements of Inconel 718 to be fulfilled in aerospace applications include that the machine surface roughness has to be less than 0.8 µm, no recast layer and the strain needs less than 10 µm [35]. However, turning and drilling machining on materials such nickel-iron based superalloys have led to the formation of a white layer on the surface [36, 37]. Kasim et al. (2003) have shown there is no white layer during machining of Inconel materials using ball nose cutting tool since the machining temperature was less than 650°C [38].

2.2. Ultrasonic Assisted Application

Azlan et al. (2016) [39] carried out the ultrasonic vibration assisted experiments to obtain the effects of machining parameters on surface roughness of hardened steel material for slot milling operation. The experiments are conducted to compare surface roughness magnitudes obtained with and without the presence of ultrasonic vibration. UAM is a machining operation that uses vibration tool oscillating at ultrasonic frequencies (18-20 kHz) and is aided by abrasive slurry that flows freely between the tool and the workpiece to remove material from the latter. The vibration tool is oscillating with amplitude 10 to 40 mm and imposes static pressure on the abrasive grains, hammered into the workpiece surface to cause chipping of fine particles and formed the required tool shape [39]. The advantage of UAM is
the great reduction in cutting force [40], in which a force of approximately 10% lower than CM has been reported [41]. By applying the ultrasonic vibration, it will increase the heat removal rate and thus increasing the tool life and decreasing the tool temperature [42]. It has also been found that the use of UAM is significantly advantageous to the productivity, which include about 30% reduction of the machining cost and 5-10% of manufacturing time [43]. Figure 9 shows the setup of UAM on the tool holder in the experiments.

![UAM setup on tool holder](image)

**Figure 9: UAM setup on tool holder: (a) by Azlan [39] and (b) by Lian [44]**

Ultrasonic machining refers to specialized ultrasonic machine tools that oscillate an abrasive tool. The Acoustech system is an application that makes use of the controlled ultrasonic vibration on any existing machining centre using any standard drill or end mill. The vibration comes from a device that is essentially a tool holder with an ultrasonic actuator built-in. The same device also incorporates a compensating vibration-cancellation mechanism that prevents the ultrasonic actuation from affecting the machine tool itself. The vibration is “ultrasonic” because its frequency is above what the human ear can hear. Audible noise occurs at 15 to 18 kilohertz. Specific effect of this vibration is expansion and contraction of the tool through controlled amplitude [12]. Tool wear still occur during application of ultrasonic vibration due to the interrupted cutting process that occurs during machining between the cutting tool and the workpiece. However, the tool wear is found to be reduced by approximately one-fifth when the UVC process is used to cut the workpiece under all cutting conditions [45].

The experimental results shown in Figure 10 are for both conventional turning (CT) and ultrasonic vibration cutting (UVC) on low alloy steel (DF2) workpiece using cubic boron nitride (CBN) inserts as the cutting tool [45]. The results are for feed rate of 0.1 mm/rev (in Figure 10(a)) and for feed rate of 0.2 mm/rev (in Figure 10(b)), where a, b, c is the cutting speeds of 50, 70, 90 m/min, respectively. It is observed that UAM can help prolong the tool life since the tool wear is lower for longer period of machining [41]. Only micro cracks in the diamond grits of the cutting tool are found after 10 m of the machining length of CFRP with UAM while in CM, grain pull-out and wear flats in the diamond grits are observed.

![Tool wears condition at three cutting speeds](image)

**Figure 10: Tool wears condition at three cutting speeds for both CT and UVC processes: (a) feed rate at 0.1 mm/rev and (b) feed rate at 0.2 mm/rev [45]**
Force is the energy required by the machining process to perform the cutting process. Since Inconel is a material that is hard to cut, high amount of energy is needed to perform the cutting process. The feed force (Fx) recorded by UAM has been shown to be up to 20% of force reduction as compared to CM on carbon fiber reinforced plastic (CFRP) using the nickel layer electroplated cutting tool with average of 420μm diamond grit [41]. The results shown in Figure 11 are the comparison of machining forces in y-direction (Fy) and feed force in x-direction (Fx) between CM and UAM. The machining force increases as the machining length is increased for both methods. During this time, the cutting tool started flaking and chipping due to interrupted cutting force phenomenon. However, the result indicates that UAM has lower machining forces through the 10m of machining length. This took place due to a larger plastically-deformed matrix transferred to the tool in CM than in UAM, causing higher obstruction in machining.

Ma et al. (2005) [43] analyzed the improvements gained with ultrasonic on a turning process using a CT. The thrust force is applied in the bending direction of the spindle, which is perpendicular to the long axis of the workpiece. Small forces from the vibration-assisted machining (VAM), with their application at ultrasonic frequencies that are well above the natural frequency of the lathe structure, is found to greatly reduce the tool tip vibration in the radial (depth of cut) direction.

A low surface finish is one of the challenging aspects to be achieved in primary machining process without undergoing any secondary or finishing process. Nevertheless, it is still possible to eliminate the finishing process when optimum machining technique is implemented. An experimental research of ultrasonic vibration assisted micro-milling on Al6061 at different amplitudes has been conducted and the results are depicted in Figure 12. This study has proven that the application of UAM improved the Ra value than that by ordinary micro-milling [44]. Machining marks can be detected on machine surface at 0μm amplitude. Figure 13 depicts overall result of the study.
From the amplitude parameter range, the minimum surface finish can be achieved at a specific amplitude. Too high or too low amplitude can cause an increase in the surface finish. The best surface roughness of 0.23 μm is obtained when the cutting amplitude at 11 μm. Further investigation has found that hammer effect induced by ultrasonic milling causes poor results. With high-frequency vibration, the cutter teeth will hammer the workpiece constantly. This result is in line with findings from another study that demonstrated as the feed increases in UAM process, the chip curvature also decreases [46]. The type of chips has an influence on the workpiece surface roughness and the findings from a study on the ultrasonic-assisted dry grinding (UADG) have led to significant improvements on the Rz and Ra parameter [47]. It is assumed that the improvement in these parameters has been due to the fact that the grit in UADG has higher chance to cut the peak of the surface due to the feed ultrasonic oscillation and increasing the possibility of interaction of the grit and workpiece surface in each contact length.

### 3. Experimental Technique and Input Parameter

Based on previous findings, machining of superalloys like Inconel 718 using CM remains a challenge until today. Many have tried to find the empirical relationship between the input and output parameters through experimental results since analytical solutions are often difficult to formulate and FEM-based solutions might take time. The combinations of cutting speed (V), feed rate (fz), depth of cut (DOC) as tabulated in Table 1 and Table 2 have been used as input parameters to analyse and predict the white layer thickness [48], surface roughness [49], residual stresses [50-53] and the yield strength of plastic strain on workpiece material [29]. Results from these studies can be applied with analytical predictions [50, 52, 54].

Since information on implementation of UAM technique is available through experimental results, analytical solutions and FEM-based solutions, the input parameter on cutting speed (V), spindle speed (n), feed rate (fz), depth of cut (DOC) and vibration frequency (f) can readily be established and also applied during the machining process. The outcomes such as tool life, cutting force and the surface roughness can be compared to those from CM process on the Inconel 718. Table 3 tabulates previous research and findings through assisted by ultrasonic vibration.

| Reference                  | Workpiece Material | Process and Cutting Tool | Parameters                          | Remarks                                                                 |
|----------------------------|--------------------|--------------------------|-------------------------------------|-------------------------------------------------------------------------|
| Derrien and Vigneau [59]   | IN-718             | Dry milling, Uncoated carbide | V = 16, 200 m/min fz = 0.04 mm/tooth DOC = 0.5 mm | Increasing V from 16-200m/min will increase the sub-surface tensile residual stress from 400-1400MPa. |
| Guerville and Vigneau [60] | IN-718             | Point milling, Uncoated carbide | V = 18, 200 m/min fz = 0.08 mm/tooth DOC = 0.2 mm | Increasing V from 18-200 m/min will increase the surface tensile residual stress from 250-750 MPa and the peak compressive residual stress from 200-450 MPa. |
| Arunachalam et al. [61]    | IN-718 (36HRC)     | Facing, CBN and mixed ceramic | V = 150-450 m/min fz = 0.15 mm/rev DOC = 0.05-0.5 mm | Increasing V will increase surface roughness and change residual stresses from compressive to tensile stress (-100 to 500 MPa) |
Table 2: Material, process and parameter information for titanium group of workpiece

| Reference            | Workpiece Material | Process and Cutting Tool | Parameters                                                                 | Remarks                                                                                                                                 |
|----------------------|--------------------|--------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Nurul-Amin et al. [55] | Ti-64              | End milling, Uncoated carbide and PCD | V = 40-160, 120-250 m/min, fz = 0.1 mm/tooth, DOC = 1 mm | For both uncoated carbide and PCD tools, increasing V from 40-160 and from 120-250 m/min, respectively, will increase the surface roughness. |
| Sun and Guo [56]     | Ti-64              | End milling, Coated carbide (TiAlN) | V = 50-110 m/min, fz = 0.06-0.14 mm/tooth, DOC = 1.5 mm | Increasing fz, tensile residual stresses at the surface increased. Surface roughness increased when the DOC increased due to increased overlap between cutting paths. |
| Ginting and Nouari [57] | Ti-6242S          | Milling, Uncoated and Coated carbide (TiN, TiC, TiCN) | V = 100-125 m/min, fz = 0.15-0.2 mm/tooth, DOC = 2-2.5 mm | Increasing V will increase the surface roughness with uncoated tools, but decrease lightly with coated tools. Increasing fz will increase the surface roughness under all cutting conditions. |
| Sridhar et al. [50]  | Ti-IMI 834         | Milling, Coated carbide (TiN) | V = 11.56 m/min, fz = 0.056, 0.1 mm/tooth, DOC = 0.25, 2 mm | At low V (11m/min), increasing fz will reduce sub-surface compressive residual stresses. At high V (56m/min), increasing fz will increase sub-surface compressive residual stresses. The compressive magnitude of residual stresses decreases when DOC is increased. |
| Mantle and Aspinwall [58] | γ-TiAl            | Milling, Uncoated carbide | V = 70-120 m/min, fz = 0.06-0.12 mm/rev, DOC = 0.2-0.5 mm | Increasing V will decrease the amount of compressive residual stresses observed.                                                   |

The general finding of these studies is that, depending on the experiments, the output parameters are found to depend heavily or slightly on the input parameters. However, through the reviews on the previous research of ultrasonic vibration assisted technique that has been employed in the milling [17], drilling [18], grinding [19] and turning [20] processes, the subsequent impact has been more positive than negative. This proves that the UAM is feasible to be explored in further study and research.
Table 3: Material, process and parameter information for machining assisted by ultrasonic vibration

| Reference          | Workpiece Material                  | Process and Cutting Tool                  | Parameters                        | Remarks                                                                 |
|--------------------|-------------------------------------|------------------------------------------|------------------------------------|-------------------------------------------------------------------------|
| Tabatabaei et al. [62] | Special conical shape for workpiece | Turning, Triangular TNMG                  | n = 1200-1400 rpm                  | Ultrasonic vibration can improve the stability for some cutting conditions while degrading the stability in some other conditions |
|                     |                                     | f = 0.3 mm/tooth                         | DOC = 5.85-9.8 mm                   |                                                                          |
|                     |                                     |                                          | f = 228.8 Hz, 20 kHz               |                                                                          |
|                     |                                     |                                          |                                    |                                                                          |
| Yasmine et al. [63]  | Soda glass                          | Milling, Diamond                         | n = 2000-10000 rpm                 | Ultrasonic vibration maximizes the axial cutting force and minimizes the moment. However, lower cutting forces are obtained in some experiments using CM |
|                     |                                     |                                          | f = 10-100 mm/min                  |                                                                          |
|                     |                                     |                                          | DOC = 0.02-0.1 mm                   |                                                                          |
|                     |                                     |                                          | f = 24.6, 25.4 kHz,                |                                                                          |
| Nor Farah Huda et al. [64] | Carbon Fibre Reinforced Plastic (CFRP) | Milling, Polycrystalline Diamond (PCD) with three cutting flute | V = 500 mm/min                   | Application of UAM resulted in reduced forces (up to 20 %) and temperatures (up to 15 %). However, surface roughness increases (up to 5 %) and higher tool wear (106 µm) compared to CM (80 µm) after 10m machining length. |
|                     |                                     |                                          | f = 0.8 mm/tooth                   |                                                                          |
|                     |                                     |                                          | DOC = 2 mm                         |                                                                          |
|                     |                                     |                                          | f = 39 kHz                         |                                                                          |
|                     |                                     |                                          | Amplitude = 5 µm                   |                                                                          |
| Abootorabi Zarchi et al. [46] | X20Cr13 Stainless Steel | Milling, 4-flute TiN coated end mill made of high-speed steel (HSS) | n = 500 rpm                   | As feed increases in UAM process, the chip curvature decreases. The chips have an influence on workpiece Ra. |
|                     |                                     |                                          | f = 0.05 mm/tooth                  |                                                                          |
|                     |                                     |                                          | DoC = 5.0 mm                       |                                                                          |
|                     |                                     |                                          | f = 16-40 kHz                      |                                                                          |
|                     |                                     |                                          | Amplitude = 2-30 µm                |                                                                          |
| Lian et al. [44]     | Al6061                              | Micro-milling Micro-milling tool (Unidentified type) | n = 150000 rpm                  | The surface processed by assisted ultrasonic vibration is more uniform than that processed by micro-milling without vibration, the latter has clear machining marks are left on the surface. |
|                     |                                     |                                          | f = 0.5 mm/s                       |                                                                          |
|                     |                                     |                                          | DoC = 5.0 mm                       |                                                                          |
|                     |                                     |                                          | f = 38 kHz                         |                                                                          |
|                     |                                     |                                          | Amplitude = 11, 15, 19 µm           |                                                                          |
| Taghi and Bahman [47] | 42CrMo4 (85 HRB)                    | Grinding, Diamond single point dresser   | V = 60 m/s                           | Assisted ultrasonic vibration reduces the grinding forces, frictional effect and plastic deformation zone. It leads to significant improvements on the Rz and Ra parameter. |
|                     |                                     |                                          | f = 500, 1000, 1500, 2000 mm/min   |                                                                          |
|                     |                                     |                                          | DoC = 0.010-0.030 mm               |                                                                          |
|                     |                                     |                                          | f = 23 kHz                         |                                                                          |
|                     |                                     |                                          | Amplitude = 10 µm                  |                                                                          |
| Ning et al. [65]     | Inconel 718                         | Laser engineered net shaping (LENS)       | V = 508, 635 m/s                  | Ultrasonic vibration on microstructures and microhardness gives lower porosity, smaller grain size, and uniform laves phases of the as-deposited Inconel 718 parts. |
|                     |                                     |                                          | hatch space = 0.3 mm               |                                                                          |
|                     |                                     |                                          | f = 0, 41 kHz                      |                                                                          |
4. Conclusion
The performance and quality of a product are influenced by surface integrity from final manufacturing processes. Surface integrity such as residual stress, microstructure and surface roughness possibly can be improved through UAM recent technique. This review paper provides an overview of machining-induced surface integrity in Inconel 718 superalloys. The following are specific conclusions reached in this review.

- UAM on the CNC milling process will improve tool life, achieve lower forces (thrust force) and improve the surface quality of a workpiece.
- In terms of the cutting forces, the maximum cutting forces observed in UAM are lower (10%) compared to CM on CFRP workpiece where tool vibration aided the material removal process in UAM.
- Reduction of cutting forces is attributed to vibration amplitude influencing the gap between the cutting tool and the workpiece material resulting in improved chip-breaking conditions.
- By applying ultrasonic vibrations on milling process makes formed chips thinner and smaller, and leads to flatter machined surface where the effect of UAM on AISI 1020 steel improves the surface roughness by up to 12.9%.
- UAM implementation can be significantly advantageous to the productivity due to reduction of about 30% of machining cost and 5-10% of manufacturing time.

The difficulties involved in CM that are addressed in UAM, improvements in machining process and the reasons for these improvements have been presented in this paper. UAM is found to be effective in advanced machining techniques in improving the process stability and quality of the products. UAM can be applied to almost all precision machining techniques. Nonetheless, the proper mechanics of the machining process to support the improvements in machining have to be developed and also studied in depth.

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