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A study on machinability of nickel based superalloy using micro-textured tungsten carbide cutting tools

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Abstract
In this research, an investigation on machinability of nickel-based superalloy (Inconel 600) under the influence of textured tungsten carbide cutting tools is conducted. Two main machinability indicators, namely, wear and life, have been investigated. Three types of micro-texture patterns i.e. dimples, lines and splines are laser engraved on the flank face of the cutting tool. Experiments are done with different cutting velocities, feed rate and depth of cut considering the texture pattern one among the input parameters. Firstly, while machining Inconel 600 with plain (non-textured) tungsten carbide cutting tool, it is investigated that at low velocity, the cutting nose caused damage due to abrasion and friction between the tool-chip interface. Severity in tool edge has increased along with adhesive wear and built-up edge at the cutting radius with increase in velocity. Thereafter, using textured on the tools, it is observed that the cutting tool wear resistance has tremendously increased with different textured patterns due to significant reduction in friction and heat. At low velocity (50 m min$^{-1}$) the tool wear measured is in the range of 100–150 $\mu$m and maximum of 394 $\mu$m at high cutting velocity of 150 m min$^{-1}$. The tool life was calculated using Taylor’s equation based on Gaussian method. Tool lives for dimple and line textures are found superior. It is concluded that textured tools have potential to machine hard materials like Inconel superalloys with longer tool life.

1. Introduction

Nickel based superalloys such as Inconel 600 are always in high demand for aero- engines, marine, nuclear plant and chemical refinery applications due to their superior properties and metallurgical behaviour at high temperature [1, 2]. It is difficult to produce a final product from these materials, as they are difficult-to-machine and possess poor machinability. It results in the form of frequent and severe tool wear, deterioration in part quality, excessive consumption of energy and lubricants, escalated machining cost and environmental footprints. Many past research and innovations have been done to enhance the machinability of these alloys, using optimum process parameter conditions, employing green lubricants and sustainable lubrication techniques, and using appropriate cutting tools etc [3, 4].

The selection of appropriate cutting tools plays a major role where their material types, geometries, and treatments etc are important factors. Cryogenic treatments, surface texturing, and coating of cutting tools have been found very effective to enhance machinability of various materials [5–7]. Pervaiz (2014) studied and reported the influence of tool material selection to machine nickel alloys [8]. Umbrello (2013) found rapid tool wear, high cutting force, and generation of excessive when machining under dry conditions [9]. The two most predominant mechanisms for cutting tool failure are (i) abrasion/friction between work-tool interface and (ii) adhesion due to plastic deformation of the material [10, 11]. Ample research has been conducted on investigation on machinability i.e. tool wear, friction force, power consumption when machining with/without lubrication [12].

During last few years, there have been accelerated research attempts towards overcoming the challenges of conventional machining, especially by tool treatment and modifying the tool surface pattern. Texture engraving
on the tool faces i.e. flank face and rake face is derived from conventional engineering of mechanical components such as oil groves in piston, coatings in bearings, and micro channels in exchangers etc [13]. These surface modifications are done to reduce friction and heat, and thereby to increase the life of the component. Surface texturing of cutting tool is done through different techniques such as: diamond cutting, spark erosion techniques, focused ion beam and with chemical erosion techniques [7, 14]. A significant reduction in the cutting tool wear has been observed by previous researchers when machining with the textured cutting tools [15, 16]. Research reports that the textures can be made either on rake face or flank face of the cutting tool inserts. It is worth mentioning that in case of tungsten carbide cutting tools, the criterion for tool failure is the amount of the wear occurred on the flank face of the tool [14–16].

From the detailed review of the existing literature, machining nickel-based superalloys using laser textured cutting tools is the major research gap identified. Frictional resistance and the wear behavior of different textures (laser engraved) on the flank face of the tungsten carbide cutting tools, and investigation on lives of the textured tools are the novelties of the proposed research.

In this research, to fulfill the research gap, three varieties of surface texture patterns have been developed on flank face of tungsten carbide cutting tools by laser engraving. Experimental investigation has been performed to study the effect of all three texture patterns and other machining parameters on tool wear when machining Inconel 600 under dry conditions.

2. Materials and method

High performance nickel–chromium based superalloy Inconel 600 is the work material. Before machining, the work material dimension was $\phi 31$ mm in diameter and 3100 mm in length with a micro hardness of 166 Hv. Commercially available SANDVIK tools, cadmium—nickel coated tungsten carbide material is used to machine the Inconel alloy. It is a CNMG12–04–04 model tool. Figure 1 presents the experimental setup and a photo image of the cutting tool inserts. The hardness of the cutting tool material 1114 Hv was six times higher than the work material.

While machining nickel alloys with any carbide cutting tools, the tool failure is due to flank wear, notch wear and built up edge formation [17]. During metal cutting, the shear force generated at the cutting edge affects flank face more than rake face. Criado et al (2018) made the same claim while machining nickel alloy with PCBN and carbide cutting tools [18]. Thus, in this work, an attempt has been made to modify flank face of the cutting tool by laser engraved textures.

Investigations are performed with surface engineered textured cutting tool. To modify the cutting tool surface area, solid state laser (Nd—YAG rod) machine (Make: Lee Laser Machine, USA; Model: SLT Q905) is used for engraving of textures on the cutting tools. Different texture patterns are made on the flank face by engraving to a depth of 50 $\mu$m for an area of $2.5 \times 2.5$ mm$^2$. Textures are made close to the cutting nose with a clearance of 150 $\mu$m on the flank face. It is to confirm that the focal diameter of the laser source used for texture pattern engraving is 1 $\mu$m. The laser nozzle travels at a speed of 100 mm per second. During the first pass, laser source penetrates the coating layer and texturing starts. On subsequent process condition, the effect of laser source evaporates the fused metal along with coating material and further does not induce any adverse thermal
effect over the tool. Moreover, it doesn’t affect the nearby tool surface area including coating. Table 1 shows the detailed information of different texture patterns and their 3D profile images.

Experiments have been conducted on FANUC CNC turning centre by varying the cutting velocity, feed rate and depth of cut. The input variable process parameters and their ranges proposed for machining Inconel 600 are given in table 2. This table also presents the composition of Inconel 600 used in the present work. A total of twenty-seven experiments have been conducted. During experimentation, the diameter of the alloy was measured before and after machining to calculate machining time. Subsequently, the worn cutting edges are observed through scanning electron microscope (SEM) to analyse the wear mechanism. Further, evaluation of machining time and tool life has been done using mathematical formulae as discussed in the subsequent sections.

3. Results and discussion

In any metal cutting process, performance of cutting tool and mechanism of tool-work interaction highly affect the machinability indicators such as surface roughness, tool wear, material removal rate, cutting force, and energy consumption etc. In this section, a detailed analysis of tool wear, and evaluation of machining time and tool life are discussed.
3.1. Analysis of tool wear

Maximum tool wear on the flank face of the cutting tool has been considered in the present work. Figure 2 shows the maximum flank wear ($V_{b_{\text{max}}}$ in $\mu m$) measured at different cutting velocities on varying the feed rate and depth of cut. While machining Inconel 600 alloy at 50 m min$^{-1}$, minimum flank wear of 115 $\mu m$ was observed for a minimum feed rate and depth of cut of 0.08 mm rev$^{-1}$ and 0.1 mm respectively. The wear found to be in increasing trend with increase in feed rate and depth of cut. At average and maximum cutting velocity (100 m min$^{-1}$ and 150 m min$^{-1}$), the difference in tool wear is found significant with higher depth of cut. However, the wear ranges are eccentric and wide in range for different feed rates. The flank wear values as presented in figure 2, are the values measured for a constant cutting length (of 50 mm) in a single stroke. To predict the wear mechanism, the worn cutting edges have been analyzed using the scanning electron microscope (SEM).

Before performing the wear analysis, an experimental trial has been conducted to cut the proposed candidate material Inconel 600 with plain carbide cutting tool (without texture). Two set of trials are made at high speed machining. The normal wear trakes in abrasive mode over the cutting nose have been observed (figure 3). The maximum flank wear measured is 278 $\mu m$ for the cutting condition 150 m min$^{-1}$–0.08 mm rev$^{-1}$–0.1 mm respectively. Here the feed rate and depth of cut are very low and simple abrasive wear scars were noticed over the cutting edge. However, with increase in feed rate (0.12 mm rev$^{-1}$) and depth of cut (0.2 mm), behavior of the cutting tool is drastic with a maximum wear of 421 $\mu m$.

In addition to this, figure 4 shows the crest like structure—built up edge due to severe plastic deformation of work metal with a mouse tail. While making a detailed investigation, it has been noticed that the adhesive wear was intricately over the rake face along with abrasive mechanism on the flank. Criado et al (2018) claims that

![Figure 2. Flank wear of tungsten carbide cutting tool measured on machining Inconel 600 alloy at different cutting velocity, feed rate and depth of cut.](image)

![Table 2. Details of input variable parameters and material composition.](table)

| Input Factors     | Unit   | Level 1 | Level 2 | Level 3 |
|-------------------|--------|---------|---------|---------|
| Cutting velocity  | m min$^{-1}$ | 50      | 100     | 150     |
| Feed rate         | mm rev$^{-1}$ | 0.08    | 0.1     | 0.12    |
| Depth of cut      | mm     | 0.1     | 0.2     | 0.3     |
| Texture pattern   | —      | Dimple  | Line    | Spline  |
| Inconel 600       |        | Ni–72%, Cr–17%, Fe–9%, C–0.15%, Mn–1%, S–0.35% and Si–0.5% |
while machining nickel-based superalloy, the tool failure is due to the friction on flank face to cause abrasive wear and adhesion of hard metal over the cutting nose were originated due to high friction [18]. That is the hardness of the cutting tool and work material Inconel 600 are in wide difference; which is nearly 1:6 in ratio [19, 20]. At a maximum process condition, friction welding has occurred with respect to high thermal gradient. To decrease these thermal gradients and welding effect, the tool textures are made over the flank face in different patterns. Based on the experimental design, wear morphology and the mechanism involved in texture patterns; line, spline and dimple are discussed in detail.

Figure 5 shows the worn cutting edge of line texture pattern on cutting tool. The wear mechanisms on line texture cutting tools are comparatively simple and better when compared to the cutting tools having other texture patterns. It is observed that machining at a process condition of 150 m min$^{-1}$, 0.1 mm rev$^{-1}$ and 0.1 mm depth of cut resulted in 282 $\mu$m flank wear. At this machining condition, the cutting edge and its nose radius alone are indulged towards plastic deformation. The built-up edge is very small compared to the plain cutting tool. In fin like arrangement (an array of line texture) over the flank face has highly influenced to reduce the friction and heat energy gradients generated during machining. These fins support to transmit the heat generated over the flank face and help to self-cooling with respect to working environment. Therefore, the thickness of adhesion was found less compared to plain cutting tool. Similar wear mechanism involved in spline textured cutting tool. Electron image of the splined cutting tool texture is given in figure 6. A minimum wear of 298 $\mu$m was noticed for the cutting condition 100 m min$^{-1}$–0.12 mm rev$^{-1}$–0.1 mm. It can be said that the spline texture effectively controlled and dissipated the heat generated during machining at this parameter setting. However, when the feed rate and depth of cut was increased, the rate of diffusion was drastic. For illustration, the wear analysis on line textured cutting tool is shown in figure 7. At a maximum feed rate and depth of cut (0.12 mm rev$^{-1}$ and 0.3 mm) revealed with similar adhesion crest in less dimension compared to plain cutting tool. Aside from the abrasion and adhesion, a dark hazy layer produced due to frictional energy and fumes produced during friction were also noticed. It confirms that, when the depth of cut and feed rate are increased, the friction force generated during machining will induce the deformed alloy to adhere over the cutting nose. It is justified with an existing research that the adhesion of bulk over the tool nose is due to the effect of metal chip deformation. The adhesion of bulk over the rake face is an unstable part and it is unavoidable on nickel alloy machining [21]. These changes are due to the deformation of bulk at a maximum cutting conditions and it can be controlled with average values of machining process parameters [22, 23]. On controlling the frictional energy, the severity in tool damage can be controlled.

Dimple texture is dislike line or spline. It is a discrete pattern developed with a thermal energy to spot circle at regular intervals. The wear behavior of dimple (discrete) texture is entirely different from continuous texture pattern. The worn edge of micro dimple textured cutting tool used to machine alloy at a combination of low velocity (50 m min$^{-1}$) and minimum feed rate (0.08 mm rev$^{-1}$) and depth of cut (0.1 mm) was examined using
electron microscope. At low cutting velocity, tool nose found with a minimum flank wear of 115 \( \mu \text{m} \) and the strong point of the tool failed due to abrasion (figure 8). Slow speed machining produces very high cutting force that may lead to severe tool wear [24]. However, at high speed machining, the intensity of the cutting force is reduced and the frictional forces are increased simultaneously. For a high-speed machining condition of 150 m min\(^{-1}\), 0.12 mm rev\(^{-1}\) and 0.2 mm, maximum flank wear of 342 \( \mu \text{m} \) was noticed. Figure 9 shows the worn section of the cutting tool edge at flank face and rake face for high speed machining with dimple textured cutting tool. Wear morphology is in the combination of adhesion, abrasion and friction which are noticed in the

Figure 4. Wear morphology on (a) flank face and (b) rake face of the plain tungsten carbide cutting tool used to machine Inconel 600 at process condition of 150 m min\(^{-1}\), 0.12 mm rev\(^{-1}\)–0.2 mm.

Figure 5. Tool wear morphology of tungsten carbide tool with line texture after machining conducted at 150 m min\(^{-1}\), 0.1 mm rev\(^{-1}\) and 0.1 mm.
flank face through scan electron microscope. While machining, cutting tool and work maintain a small angular clearance of 6° for both rake angle and relief angle. The friction energy generated between the work-chip-tool has been disseminated through the continuous (line and spline) textured tool. However, in dimple textured tool, rate of heat energy developed due to friction has been ascertained at the dimples and micro crake were induced. While machining, the work material with less hardness gets yielded and deformed to adhere over the rake face. The effect of frictional energy also influenced the materials to shear fast and adhere layer—by—layer at the rake face. Image represent in rake face reveals like serrated chips generated at high shear force in addition to adhesion, the flank face is prone to abrasive wear. However, the sliding of metal chips in between the work and cutting tool clearance angle has also influenced to damage the flank face in cutting tool. Figure 10 shows the mechanical action of hard metal chips over the dimple texture observed at higher magnification. A thermal crake has been
noticed in line to the dimple of the textured cutting tool. When the contact area is increased, the rate of friction found is more. Moreover, the flank face has high wear scars in line to the chip / work flow direction. This observation is confirmed with existing literature [25]. Hence, the inference on wear analysis and its electron images confirm that the tool wear can be with continuous textured pattern. Continuous textures are supporting to reduce the friction, heat gradient and subsequently minimum tool wear at appropriate cutting conditions.

3.2. Evaluation of machining time and tool life
The performance of cutting tool, and its failure while machining any material have direct influence on machining time, tool life and machining cost. Machining time for any process condition can empirically be
calculated using volume of material removal and its material removal rate. The mathematical relation for machining time calculations are given below:

\[
\text{Volume of material removed (V)} = \frac{\pi}{4}(D_{avg}^2 - D_i^2)l
\]

Material removal rate (MRR) = \(v_{avg}fd\)

Average cutting velocity\((v_{avg}) = \pi D_{avg}N\)

Average diameter\((D_{avg}) = \frac{(D_o - D_i)}{2}\)

Machining time\((T_m) = \frac{V}{MRR}\)

The machining time (min) calculated for individual process parameters are plotted in figure 11. To perform machining, minimum cutting velocity requires maximum time and it decreases with reference to increase in cutting velocity. Similarly, at low feed rate, the distance travelled to remove the bulk of metal remains less and at higher feed rate, the traverse speed of the tool is high. While considering the depth of cut, the variation in machining time may be very significant and it directly results on increase in material removal rate and tool wear as well. In this proposed design of experiments, at high cutting velocity, the machining time fits in the same line with respect to feed rate and depth of cut. For the minimum and average cutting velocities, machining time was noticed with nominal differences at corresponding feed rate. Especially, at low feed rate, the machining time differs with varying depth of cut. As mentioned, the material removal rate is highly dependent on the depth of cut.

From the machining time, the life of cutting tool was calculated through Gaussian Elimination method following multi-regression equation using SYSTAT software. Literature reports that to derive the ideal tool life equation for any turning process, cutting velocities and feed rates are the major factors to be considered [19]. In this case, the tool lives for the individual texture patterns are studied and the corresponding equations are shown in table 3. Adjacent to the Taylors equation, the data used to evaluate tool life with multiple regression equation has proved that the experimental design are fitting to a linear curve with \(R^2\) (coefficient of determination) values as given in table 3. For all the three textured cutting tools, the proportion of response is above 86% and it fits linear to the process variables. Using the Taylors equation, the tool life is calculated and plotted in graph (figure 12) at varying cutting velocity/speed with constant depth of cut. As discussed in the wear analysis, the dimple textured cutting tool performed better at low cutting velocity (50 m min\(^{-1}\)) and the same reflected here with maximum tool life of 15.34 min at feed rate of 0.08 mm rev\(^{-1}\). At a maximum velocity 150 m min\(^{-1}\), the tool lives of all the three textured patterns are in the range of 1–1.23 min. Subsequently, the increasing feed
rate decreased tool lives. For the same cutting velocity 50 m min\(^{-1}\), the tool life varies from 15.34 min to 8.44 min for 0.1 mm rev\(^{-1}\) and 5.18 min for 0.12 mm rev\(^{-1}\).

Therefore, proposed research on textured cutting tool clearly describes that the continuous textured pattern is suitable to reduce the friction and thermal energy generated during machining. These textures are also influencing to reduce tool failure due to abrasion and adhesion. It is to conclude that the spline and line texture can machine any hard material at high speed machining in a defined process condition.

3.3. Discussion

The nickel alloy Inconel 600 was machined with different textured patterns of carbide cutting tools at different process conditions. The plain carbide cutting tool used to cut Inconel 600 has produced severe flank wear due to high friction. While machining superalloy, the dominant tool wear is in the form of abrasion on flank face and it has been verified with the existing research work [26–28]. Since the cutting tool edges are laser textured to reduce friction between the work and cutting tool interface. From the experimental results; a detailed analysis on flank wear, wear morphology and tool life has been done. A very high influence of machining process parameters on tool wear is found. The result shows that the performance of textured tool is superior when compared to plain cutting tool. The tool flank wear is progressive with increase in cutting velocity. The changes in tool wear is due to variation in cutting velocity and feed rate.

At high speed machining the deformed metal chips found attached over the cutting nose (of plain cutting tool) and it is due to the frictional heat and weldability of superalloy [28]. The length of abrasive wear scars varies with reference to process parameter [29]. At higher cutting velocity (150 m min\(^{-1}\)–0.12 mm rev\(^{-1}\)–0.3 mm), both abrasive wear and adhesive wear are more. However, the rate of adhesion found less in spline textured tools.

![Figure 11. Calculated machining time (min) with respect to cutting velocities at different feed rate and depth of cut.](image-url)
due to their high heat dissipation capability than line textured tools. However, in dimple textured tool, wear phenomena is found different to continuous textures (line/spline) and has produced abrasion over flank face. A standard Taylors equation proves that the life of continuous texture tool has maximum life compared to the dimple pattern. Therefore, based upon the investigation results and their analysis, it can be concluded that on the basis of machining time and flank wear, continuous textured carbide tool is recommended to machine superalloy at a maximum cutting velocity of 150 m min$^{-1}$ with average feed rate and depth of cut of 0.1 mm rev$^{-1}$ and 0.2 mm respectively.

4. Conclusions

Effect of differently engraved texture patterns on tool wear during machining of nickel-based superalloy Inconel 600 is reported in this paper. The following conclusions can be drawn from this work-

1. At minimum cutting velocity of 50 m min$^{-1}$ the tool wear measured are in the range of 100–150 $\mu$m and 394 $\mu$m for 150 m min$^{-1}$. Increase in cutting velocity increases the generation of forces during machining that leads to tool damage and wear. The plain cutting tool has a maximum tool wear of 421 $\mu$m at 150 m min$^{-1}$–0.12 mm rev$^{-1}$.

2. The flank wear measured on the textured cutting tools are very less compared to plain tool. As texture patterns significantly reduced friction, managed heat generation and minimized wear during machining of Inconel 600.

3. The cutting velocity and feed rate are the predominant factors for tool life and machining time. Based on Taylor equation derived, the life of cutting tool is maximum (15.34 min) with a slow speed machining and minimum (1.23 min) for high speed machining. There is not much deviation with texture design except wear mechanism.

4. The textured tool failure at 150 m min$^{-1}$ is a reasonable wear which is acceptable for finish machining process (<400 $\mu$m). Therefore, the textured tool as selected in this research can also be explored for machining at high speed.

5. The lives of the tools with continuous texture patterns i.e. spline and line are maximum and these tools are highly reliable to control the friction than the dimple textured cutting tools.

Therefore, the continuous textured tool are highly recommended to machine hard metals and alloys at an average cutting velocity and feed rate.

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