

Comparison of conventional drilling and helical milling for hole making in Ti6Al4V titanium alloy under sustainable dry condition

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Abstract. Hole drilling in Ti6Al4V titanium alloy is challenging due to its poor machinability resulting from high-temperature strength and low thermal conductivity. Therefore, an evaluation of the helical milling process is carried out by comparing the thrust force, surface roughness, machining temperature, burr size, and hole diametrical accuracy with the conventional drilling process. The results indicate the advantage of the helical milling in terms of the lower magnitude of thrust force. The holes generated using helical milling displayed a superior surface finish at lower axial feed conditions, while higher axial feed conditions result in chatter due to the tool deformation. Also, the absence of a heat-affected zone (HAZ) under dry helical milling conditions indicates the work surface formation without thermal damage. Besides, a significant reduction in the size of the burrs is noted during helical milling due to lower machining temperature. Analysis of the hole diameter reinforces the capability of the helical milling process for processing H7 quality holes. Consequently, helical milling can be considered a sustainable alternative to mechanical drilling, considering its ability to machine quality holes under dry machining conditions.

Keywords: Ti6Al4V titanium alloy / helical milling / drilling / force / surface roughness / temperature

1 Introduction

Properties like high strength to weight ratio, fatigue life, yield strength, relatively high resistance to corrosion and temperatures, unique to titanium alloys make them a desirable material in many manufacturing industries [1,2]. In the aviation industry, titanium alloys are used explicitly as structural materials [3], where a considerable number of holes are required for assembling the fuselage by employing bolts or rivets. A report briefs that around 180 000 holes are processed in a single Airbus 380 wing box [4], and in an aircraft assembly, hole-making comprises 40–60% of the total material removal process [5,6]. Typically, conventional drilling is the most acclaimed process for making holes for structural assembly.

Implementation of dry machining is beneficial as it is a sustainable process that can reduce production costs and increase productivity [7]. However, the machining of titanium alloys poses several challenges. From the material point of view, titanium alloys demonstrate very poor machinability due to their high reactivity leading to cold welds and premature tool failure [6]. Besides, the low thermal conductivity characteristics can lead to a rapid

rise in temperature and massive material adhesion, resulting in catastrophic cutting tool failure [8]. Moreover, high strength at elevated temperatures also impairs the material machinability [9]. From the perspective of the manufacturing process, conventional drilling has several drawbacks. The continuous work-tool contact translates to increased thrust force and excessive heat generation. The resulting friction can deteriorate the surface finish of the hole [10], which can, in turn, initiate fatigue cracks by acting as stress concentration zones [9,11]. The drilling of titanium alloys also results in undesirable burr formation [12], inferior dimensional accuracy in terms of roundness and cylindricity [10]. Also, the heat-affected zone during dry drilling can induce undesirable microstructural changes [13,14].

Lately, helical milling has emerged as a substitute for machining holes in difficult-to-machine materials. The process was noted to generate holes with a superior surface finish while machining AISI D2 tool steel [15]. The cutting force magnitude was reported to be considerably lower even while machining GH4169 nickel-based superalloy [16]. Also, dry helical milling of AISI H13 hardened steel revealed a possible improvement in productivity. But very high cutting speed resulted in tool nose fracture and large-sized burr formation at hole exit [17]. Experimental investigation on helical hole milling of nickel superalloy

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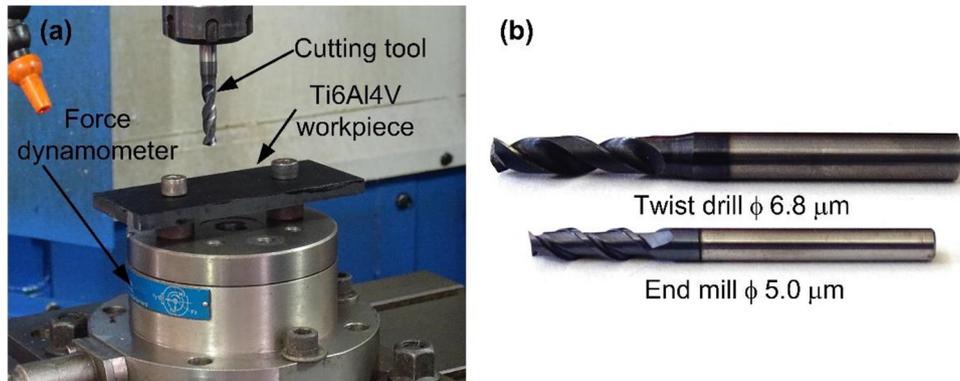


Fig. 1. (a) Experimental setup, (b) Cutting tools.

(MSRR7197) showcased the advantages in terms of lower cutting forces, reduced tool wear, and enhanced surface finish [18]. Minimum Quantity Lubrication (MQL) assisted machining also helped improve the surface quality and diametrical accuracy during helical milling of AISI 4340 steel [19]. Hole processing in carbon fiber reinforced epoxy (CFRP) laminates also showed significant improvement in the hole quality due to reduced cutting forces [20,21]. Further, the helical milling process was successful in generating quality holes in hybrid CFRP/Ti stacked laminates [22,23].

Considering the difficulties associated with hole drilling in titanium alloys, researchers have examined the utility of the helical milling process. The implementation of the helical milling process was successful in lowering the cutting forces and improving the surface finish in Ti6Al4V titanium alloy [24]. The tool wear aspects during helical milling were analyzed extensively, considering the process kinematics. The results showed that chipping, diffusion, and oxidation were the prominent wear mechanisms leading to tool failure. Also, material smearing onto the machined surface was noted [25]. Hole milling using a TiAlN coated tool helped improve the tool life and surface finish [26]. Helical milling of titanium alloy using a slender end mill was found to elicit low dimensional accuracy due to tool deformation [27]. Improvement in the surface finish while machining at low feed and cutting speed values has been reported. High cutting speeds diminished the surface quality due to thermal damage resulting from elevated cutting temperatures. Moreover, an increase in the cutting temperature led to adhesion and diffusion types of wear [28]. Microstructure and the fatigue performance analysis during helical hole milling of Ti6Al4V titanium alloy displayed less severe plastic deformation and longer fatigue life [29]. A preliminary study that compared the drilling with the helical milling process indicted the advantages of helical milling in terms of lower forces, machining temperature, surface roughness, and lower dimensional deviation [30]. A recent report suggested that down milling, coupled with higher tangential feed, helped improve the surface finish. But the authors were unable to effectively analyze the influence of process parameters on burr formation [31]. Further, the analysis of surface roughness and chip morphology analysis while machining Ti-6Al-4V

and Ti-6Al-7Nb titanium alloys showed that Ti-6Al-7Nb presented lower roughness as compared to Ti-6Al-4V alloy at a lower axial pitch and feed values [32].

It is evident from the available literature that the helical milling process is suitable for processing holes in difficult-to-machine materials. But the communications relating to the helical milling of titanium alloys are restricted mainly to hole quality analysis. The availability of a comprehensive study comparing the drilling process with helical milling of titanium alloy in the public domain is still limited. Also, the analysis of machining temperature and burr formation during the helical milling of titanium alloy has not received adequate attention. Therefore, a detailed study was imminent to analyze the performance of helical milling and uncover its merit over the conventional drilling process. Thus, in the present study, holes were processed in Ti6Al4V titanium alloy using the drilling and helical milling process, and a comparative analysis was carried out considering the thrust force, surface finish, diametrical accuracy, machining temperature, and burr size under dry cutting condition.

2 Materials and methods

Figure 1a shows the setup used to conduct the experiments. For the comparison, holes of 6.8 mm diameter were processed on the Ti6Al4V titanium alloy plate, having a dimension of 120 mm × 60 mm × 7 mm. The holes were processed under the dry cutting condition on a three-axis CNC (AMC Spark), with a maximum spindle speed of 8000 rev/min. The drilling experiments were conducted using 6.8 mm solid carbide drill bits, while the helical milling operation was performed using 5 mm two-fluted end mills seen in Figure 1b.

The axial force was measured using an accelerometer-based dynamometer (Kistler – 9272) system. The hole surface roughness was measured using a Perthometer (Taylor Hobson – Surtronic 3+). The surface roughness was measured at six locations, and the average value was considered. The surface texture was captured using an optical microscope (Olympus – BX53M). The machining temperature was measured and assessed using an infra-red (IR) thermal image analyzer (Fluke – Ti32). The processed hole dimension deviation was measured with a

Table 1. Experimental control parameters and estimated machining time.

| Case | Cutting speed (m/min) | Axial feed (mm/rev) | | Tangential feed (mm/tooth) | Machining time (s) | |
|------|-----------------------|---------------------|-----------------|----------------------------|--------------------|-----------------|
| | | Drilling | Helical milling | Helical milling | Drilling | Helical milling |
| 1 | 20 | 0.015 | 0.20 | 0.075 | 87 | 91 |
| 2 | 20 | 0.030 | 0.35 | 0.075 | 51 | 53 |
| 3 | 20 | 0.045 | 0.50 | 0.075 | 39 | 41 |
| 4 | 40 | 0.015 | 0.20 | 0.075 | 51 | 53 |
| 5 | 40 | 0.030 | 0.35 | 0.075 | 33 | 34 |
| 6 | 40 | 0.045 | 0.50 | 0.075 | 27 | 28 |
| 7 | 60 | 0.015 | 0.20 | 0.075 | 39 | 40 |
| 8 | 60 | 0.030 | 0.35 | 0.075 | 27 | 27 |
| 9 | 60 | 0.045 | 0.50 | 0.075 | 23 | 23 |
| 10 | 80 | 0.015 | 0.20 | 0.075 | 22 | 22 |
| 11 | 80 | 0.030 | 0.35 | 0.075 | 19 | 20 |
| 12 | 80 | 0.045 | 0.50 | 0.075 | 15 | 17 |

coordinate measuring machine (CMM) (Mitutoyo Crysta Plus M700). For a meaningful comparison, the process parameters were selected considering parity in productivity (material removal rate). Therefore, for a fixed cutting speed value, the feed value is chosen such that the time needed to machine each hole would be similar for both drilling and helical milling. Table 1 presents the details of the control parameters used in the study. As evident, the average processing time for each hole is similar between the two methods. The experiments were repeated thrice, and the average values of the performance measures were considered for analysis.

3 Results and discussion

The measured values of performance indicators for the drilling and helical milling process are listed in Tables 2 and 3, respectively.

3.1 Analysis of axial thrust force

High axial thrust force can result in tool deformation, vibration and affect the diametrical accuracy and surface finish of the processed holes [29]. Therefore, the thrust force developed during the drilling and helical milling is analyzed. Figure 2 shows the plots comparing the thrust force obtained during drilling and helical milling (Case 7). The thrust force component is noted to be higher for the hole processed using mechanical drilling. The thrust force magnitude is 332.4 N during drilling, while helical milling reports a force of 73.91 N under similar productivity conditions. The higher thrust force value during drilling is attributed to the machining mechanism. At the chisel edge, the work material is parted-off contrary to the shearing action, consequently increasing the thrust force during entry. Also, the majority of the cutting takes place at the frontal cutting edges (lips), thus directing the force axially. Moreover, excessive plastic deformation while machining titanium alloys results in work hardening. The increase in

hardness elevates the magnitude of the thrust force [33]. However, during helical milling, material removal takes place by shearing. In addition, the use of axial and peripheral cutting teeth for material removal distributes the cutting load. As a result, the thrust force is comparatively lower in the case of helical milling.

Further, the variation of thrust force with the cutting speed and axial feed is analyzed. For both the processes, the thrust force decreases as the cutting speed increases from 20 to 80 m/min (see Fig. 3a and b). At a higher cutting speed value (80 m/min), the material undergoes excessive plastic deformation, resulting in increased machining temperature. Due to the high machining temperature, the material undergoes thermal softening, thus lowering the thrust force magnitude [34]. Figure 3c and d describes the thrust force variation with the axial feed. The thrust force increases with the increasing axial feed values. The magnitude of thrust force is highest when the feed is highest for drilling (0.045 mm/rev) and helical milling (0.5 mm/rev). There is an increase in uncut chip thickness at higher axial feed values, which results in increased force value. Overall, the force comparison reveals that the drilling process forces are 4–7 times higher than the helical milling process. The substantially lower forces during helical milling thus exemplify the advantage of the process.

3.2 Analysis of surface roughness

The machined surface quality is an important parameter that determines the application and functionality of the components under dynamic loading conditions. Therefore, the surface roughness of the holes processed using drilling and helical milling is analyzed. Figure 4 illustrates the microscopic view and the 2D profiles of the hole surfaces processed using the drilling and helical milling (Case 5).

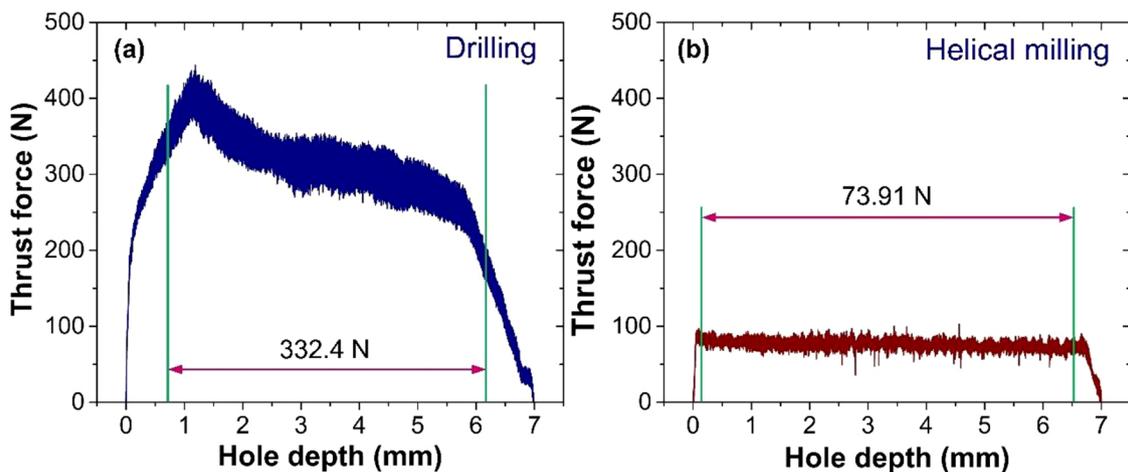
Visual inspection reveals a higher roughness in holes generated using conventional drilling, as seen from Figure 4a. Higher surface roughness in hole drilling is attributed to two reasons. Hole drilling produces continuous chips (see Fig. 5a), which are strain hardened due to

Table 2. Response data for various combinations of drilling parameters.

| Case | Cutting speed (m/min) | Axial feed (mm/rev) | Thrust force (N) | Surface roughness (μm) | Machining temperature ($^{\circ}\text{C}$) | Entry diameter (mm) | Exit diameter (mm) |
|------|-----------------------|---------------------|------------------|-------------------------------------|--|---------------------|--------------------|
| 1 | 20 | 0.015 | 371.2 | 1.84 | 305.9 | 6.8215 | 6.8208 |
| 2 | 20 | 0.030 | 491.3 | 2.11 | 357.0 | 6.8313 | 6.8256 |
| 3 | 20 | 0.045 | 569.9 | 2.47 | 377.1 | 6.8352 | 6.8305 |
| 4 | 40 | 0.015 | 350.5 | 1.53 | 368.2 | 6.8196 | 6.8184 |
| 5 | 40 | 0.030 | 441.9 | 1.95 | 380.7 | 6.8278 | 6.8234 |
| 6 | 40 | 0.045 | 531.7 | 2.06 | 394.0 | 6.8309 | 6.8277 |
| 7 | 60 | 0.015 | 331.1 | 1.36 | 395.2 | 6.8180 | 6.8172 |
| 8 | 60 | 0.030 | 435.8 | 1.53 | 434.0 | 6.8237 | 6.8203 |
| 9 | 60 | 0.045 | 525.4 | 1.79 | 491.2 | 6.8301 | 6.8232 |
| 10 | 80 | 0.015 | 307.4 | 1.28 | 439.8 | 6.8136 | 6.8163 |
| 11 | 80 | 0.030 | 418.1 | 1.37 | 472.1 | 6.8211 | 6.8189 |
| 12 | 80 | 0.045 | 496.3 | 1.46 | 513.6 | 6.8267 | 6.8206 |

Table 3. Response data for various combinations of helical milling parameters.

| Case | Cutting speed (m/min) | Axial feed (mm/rev) | Thrust force (N) | Surface roughness (μm) | Machining temperature ($^{\circ}\text{C}$) | Entry diameter (mm) | Exit diameter (mm) |
|------|-----------------------|---------------------|------------------|-------------------------------------|--|---------------------|--------------------|
| 1 | 20 | 0.20 | 87.58 | 0.48 | 99.7 | 6.8141 | 6.8134 |
| 2 | 20 | 0.35 | 98.63 | 0.62 | 131.6 | 6.8168 | 6.8156 |
| 3 | 20 | 0.50 | 114.8 | 0.75 | 153.6 | 6.8196 | 6.8179 |
| 4 | 40 | 0.20 | 77.38 | 0.65 | 139.3 | 6.8125 | 6.8113 |
| 5 | 40 | 0.35 | 80.43 | 0.81 | 169.8 | 6.8146 | 6.8137 |
| 6 | 40 | 0.50 | 83.92 | 0.87 | 181.0 | 6.8177 | 6.8145 |
| 7 | 60 | 0.20 | 72.86 | 0.87 | 177.7 | 6.8095 | 6.8082 |
| 8 | 60 | 0.35 | 76.85 | 1.27 | 207.9 | 6.8114 | 6.7991 |
| 9 | 60 | 0.50 | 77.38 | 1.24 | 226.9 | 6.8140 | 6.7971 |
| 10 | 80 | 0.20 | 65.71 | 1.06 | 224.3 | 6.8091 | 6.8068 |
| 11 | 80 | 0.35 | 70.80 | 1.32 | 253.5 | 6.8099 | 6.7980 |
| 12 | 80 | 0.50 | 72.14 | 1.41 | 274.4 | 6.8107 | 6.7972 |

**Fig. 2.** Axial thrust force plot for (a) Drilling, (b) Helical milling.

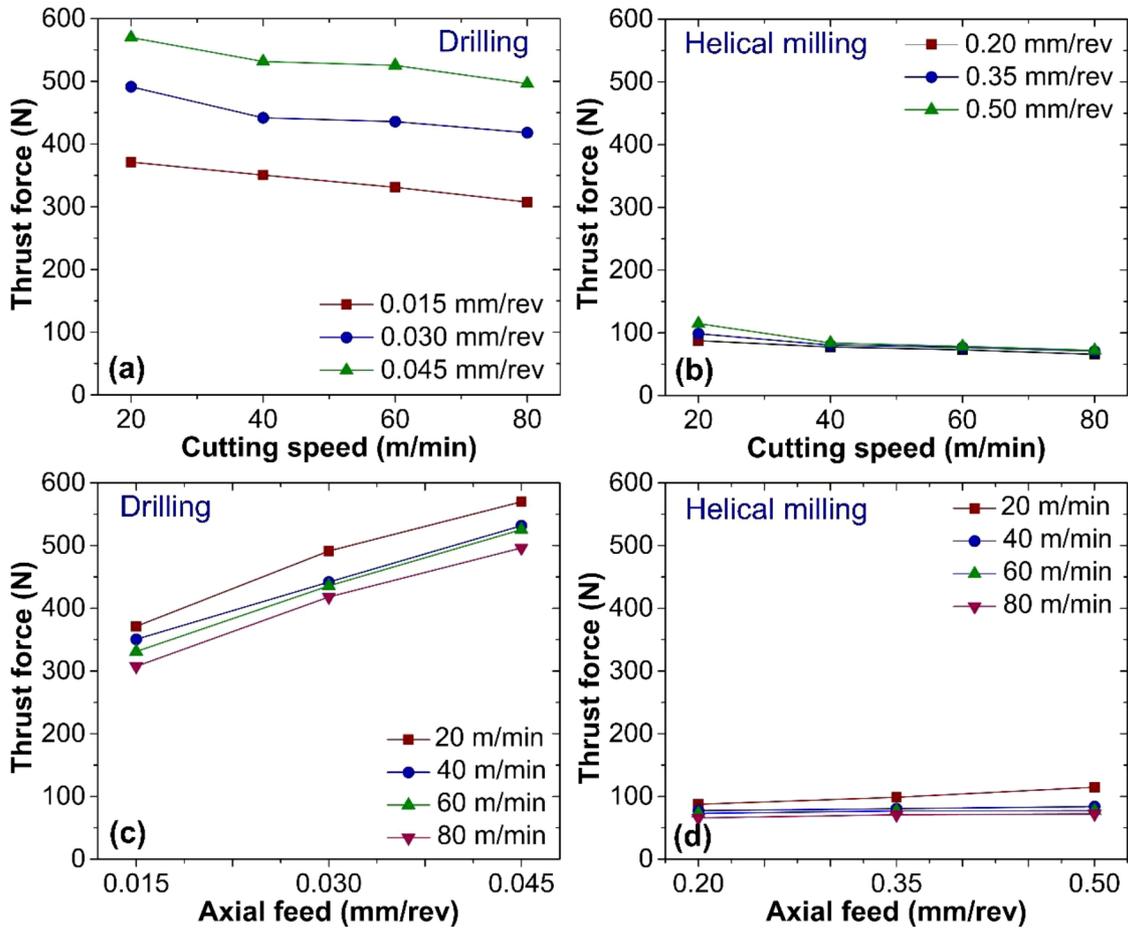


Fig. 3. (a) Thrust force vs. cutting speed during drilling, (b) Thrust force vs. cutting speed during helical milling, (c) Thrust force vs. axial feed during drilling, (d) Thrust force vs. axial feed during helical milling.

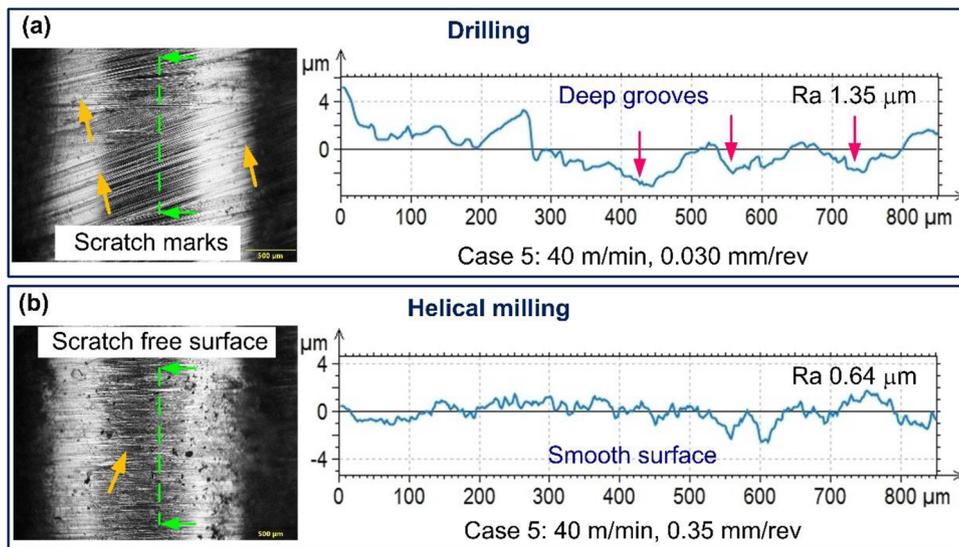


Fig. 4. Microscopic view and the 2D profile of the hole surface processed using (a) Drilling, (b) Helical milling.

plastic deformation. These continuous chips obstruct the cutting operation by entangling around the helical drill (see Fig. 5b). While being evacuated through the drill flutes, the

chips rub against the surface of the machined hole. The secondary cutting action results in deep grooves and scratches, thus damaging the hole surface and deteriorat-

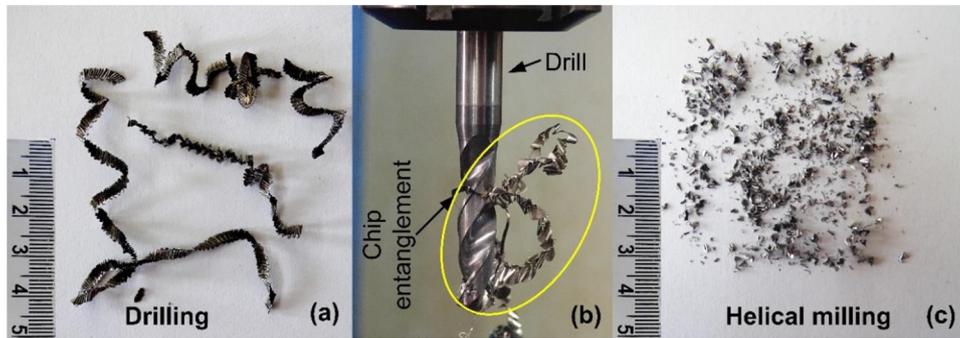


Fig. 5. (a) Chip during drilling process, (b) Chip entanglement during drilling, (c) Chips during helical milling process.

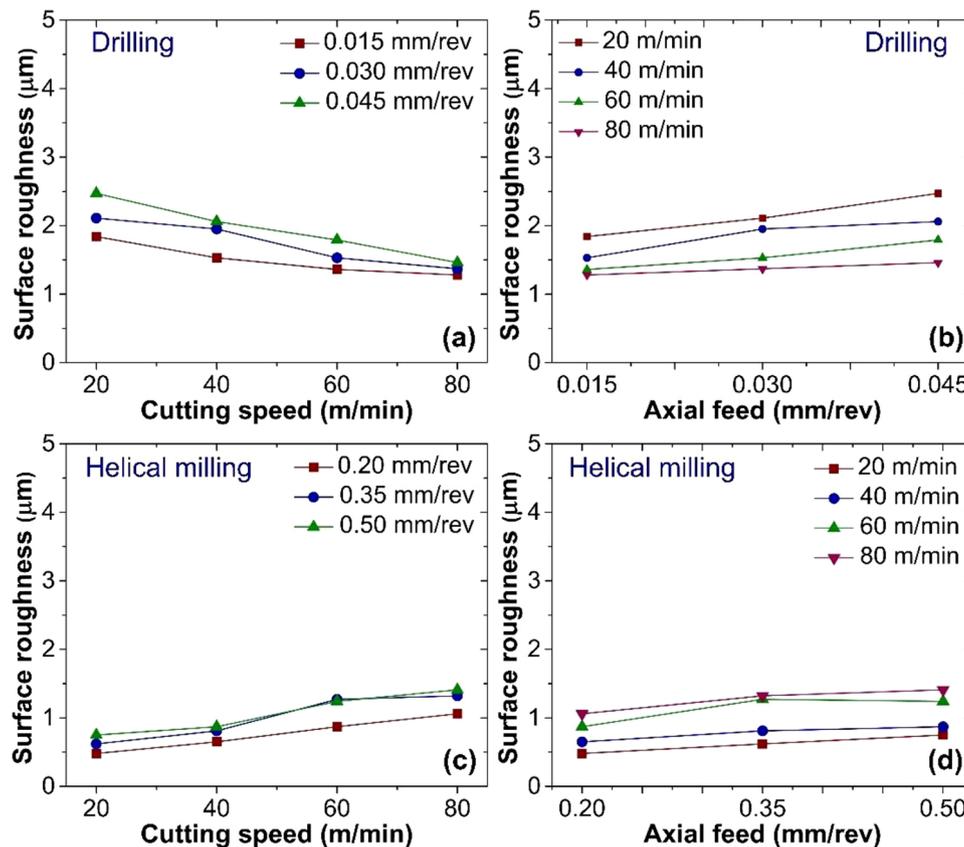


Fig. 6. (a) Surface roughness vs. cutting speed during drilling, (b) Surface roughness vs. cutting speed during helical milling, (c) Surface roughness vs. axial feed during drilling, (d) Surface roughness vs. axial feed during helical milling.

ing the surface finish. Also, the instability due to the tool deflection resulting from high axial force can degrade the surface finish [15]. In comparison, the roughness of the surface machined using helical milling is lower, as seen from Figure 4b. In the case of helical hole milling, the cutting action is intermittent in nature. Consequently, discontinuous chips are formed (see Fig. 5c), thus reducing the chip contact with the machined hole surface. Additionally, free space between the tool and borehole due to the smaller tool diameter helps in the effective evacuation of the chips, thereby preventing surface-to-surface contact and scratching of the machined surface.

Further, the effects of cutting parameters on surface roughness are analyzed. Figure 6a and b illustrate the influence of control parameters on surface roughness during mechanical drilling. The surface roughness reduces with the increase in cutting speed but increases with the increase in feed value. As seen in Figure 7a–c, for all the levels of axial feed (0.015–0.045 mm/rev), drilling at 20 m/min results in poor surface finish due to the presence of scratch marks formed by the strain hardened chips evacuating through the twist drill. Drilled hole surfaces at higher cutting speed (40 m/min) and lower axial feeds (0.015–0.030 mm/rev) show the presence of scratch marks,

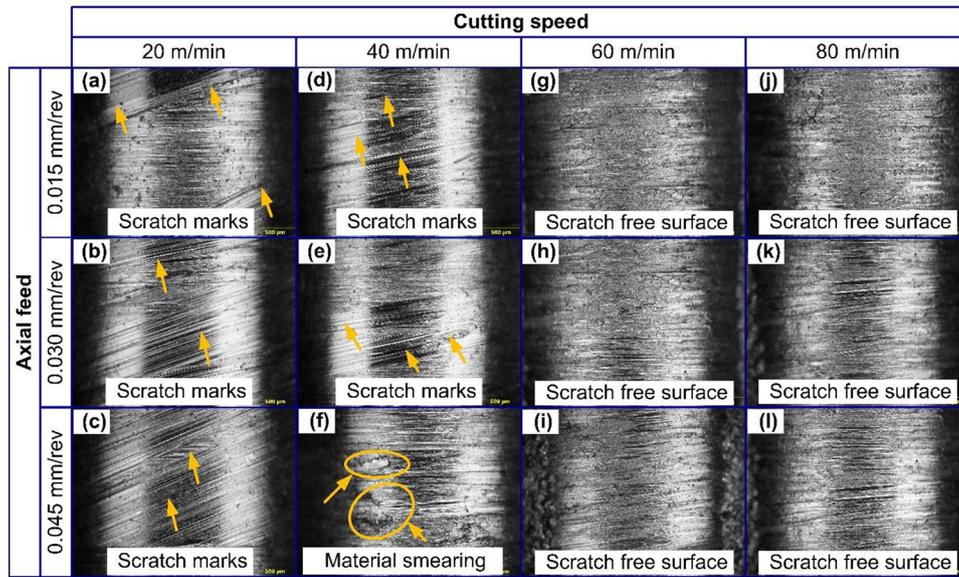


Fig. 7. Surface roughness during drilling for various cutting speeds and feed combinations.

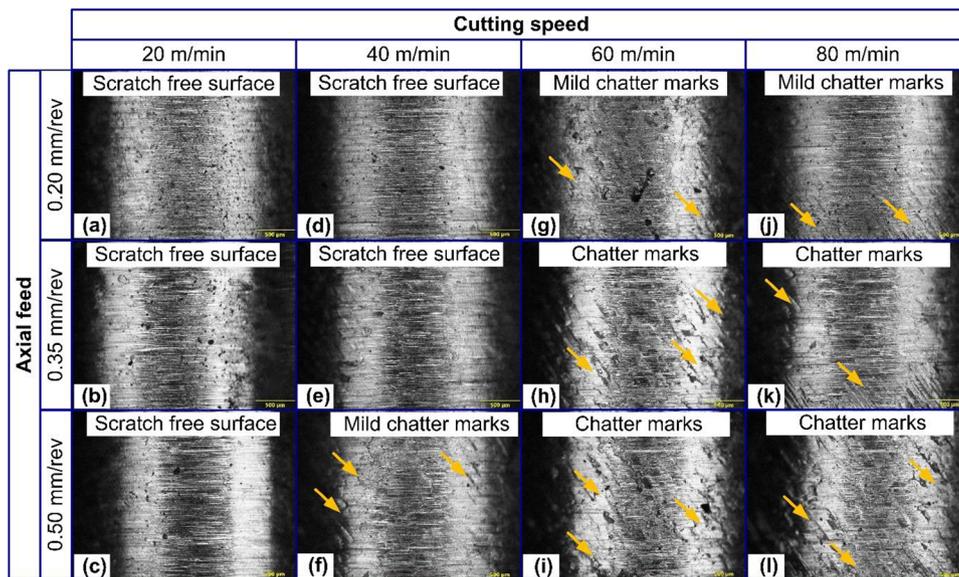


Fig. 8. Surface roughness during helical milling for various cutting speeds and feed combinations.

indicating a lower surface finish as illustrated by Figure 7d and e. But, drilling at an axial feed of 0.045 mm/rev shows a reduction in surface scratches, but microscopic observation reveals the presence of adhered material (Fig. 7f). However, drilling at higher cutting speeds (60–80 m/min) is beneficial due to the significant improvement in the hole surface quality, as seen from Figure 7g–l. Elevated machining temperatures at high cutting speeds lower the material yield stress. This facilitates a reduction in the friction and milling force, thereby improving process stability and surface finish [35].

Compared to the drilling process, the surface roughness during the helical milling process shows an interesting trend. As seen in Figure 8c and d, the surface roughness increases with the increase in cutting speed

and axial feed values. The holes processed at a lower value of cutting speed (20 m/min) show scratch-free machined surface for all the levels of the axial feed (0.2–0.5 mm/rev) (see Fig. 8a–c). Since the borehole diameter is larger than the end mill, sufficient free space is available for the chips to evacuate, thus preventing the chips from scratching the machined surface. Machining at a cutting speed of 40 m/min, the roughness of the surface is lower at lower axial feed conditions (see Fig. 8d and e). However, an increase in the feed to 0.50 mm/rev shows a reduction in surface finish due to the formation of mild chatter marks (see Fig. 8f). Similar observations are made at a higher cutting speed (60–80 m/min) and lower feed combination (0.2 mm/rev) as seen from Figure 8g and j, respectively.

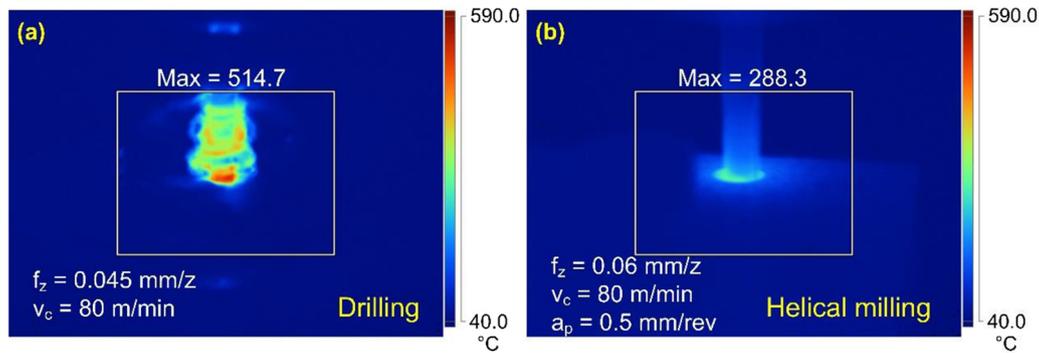


Fig. 9. IR thermograph for (a) Drilling, (b) Helical milling.

However, contrary to the work reported by Barman et al. [30], at higher cutting speed (60–80 m/min) and feed combinations (0.35–0.5 mm/rev) formation of dominant chatter marks are evident (see Fig. 8h, i, k, and l). The chatter patterns are noted at the exit end of the holes. The generation of chatter can be attributed to unstable machining at high feed conditions. At high feed value, there is an increase in the uncut material being cut. As a result, the chip load increases, causing the slender tool to deflect and generate chatter marks.

3.3 Analysis of machining temperature

Very high machining temperature has a detrimental effect on the machining process as it might lead to dimensional inaccuracy, reduced life of the cutting tool, induction of residual stresses, and workpiece surface/subsurface damage. Therefore, lower temperatures must be maintained during machining operations. Hence the temperature developed during the drilling and helical milling process is compared and analyzed. Figure 9 depicts the IR thermal images obtained for the two processes under similar productivity conditions (Case 12).

For the holes processed under similar productivity conditions, the maximum temperature noted during the drilling process is 514.7°C. Meanwhile, the maximum machining temperature during the helical milling is 288.3°C. The temperature during drilling is around 1.8 times higher in comparison to the helical milling process. The higher temperature magnitude noted during mechanical drilling can be ascribed to the process mechanics. There exists a constant continuous contact between the drill and the work surface. The resulting frictional heat adds to the heat generated due to the plastic deformation, thus increasing the machining temperature. Additionally, the poor thermal conductivity of the titanium alloy prevents adequate heat dissipation, thus contributing to the temperature rise. In comparison, the intermittent nature of the work-tool contact in helical milling is helpful since the chips which carry away the heat can be evacuated easily without any increase in frictional load, thereby preventing any drastic temperature rise.

Additionally, the influence of process parameters on machining temperature is analyzed. Figure 10 graphically depicts the variation in machining temperature with

cutting speed and feed values for the two processes. As seen from Figure 10a, machining temperature increases with the cutting speed during conventional drilling. With the increase in cutting speed from 20 to 80 m/min, the plastic and friction deformation rate increases. Consequently, the rate of heat generation also increases. Also, low thermal conductivity restricts the material's ability to conduct and dissipate the heat, thus increasing the temperature at the cutting zone. Helical milling shows a similar increasing trend with the increase in cutting speed from 20 to 80 m/min, as seen from Figure 10b. But the magnitude of the machining temperature is substantially lower. As discussed, the intermittent contact between the end mill and the workpiece reduces the frictional thermal load. Also, the production of discontinuous chips lowers the chip-tool contact, thereby lowering the machining temperature. Figure 10c illustrates the variation in machining temperature with axial feed during the drilling process. The machining temperature increases with the increase in the axial feed value from 0.015 to 0.045 mm/rev. At high axial feed, an increase in the tool-workpiece contact increases the friction and stress state, thus elevating the machining temperature. A similar increasing trend is observed during helical hole milling as the feed value increases from 0.2 to 0.5 mm/rev (see Fig. 10d). But the magnitude of machining temperature is considerably lower than the drilling process.

Figure 11a shows the drilled hole under high cutting speed and feed conditions (Case 9). Closer microscopic observation reveals a change in the color of the work material at the vicinity of the drilled holes. A color change at the periphery of the drilled hole suggests the presence of a heat-affected zone (HAZ). The blue color indicates high-temperature build-up and localization of heat near the machined hole surface. The phenomenon can be attributed to the low temperature conducting capability of the titanium alloy. Such a condition is undesirable since it can alter the microstructure around the hole surface [14]. In comparison, no such color change is observed during helical milling (see Fig. 11b), indicating lower machining temperature. A study on the microstructural changes in the work material due to high machining temperature is essential and warrants a separate investigation. But the preliminary results further help ascertain the advantage of helical milling over the mechanical drilling process.

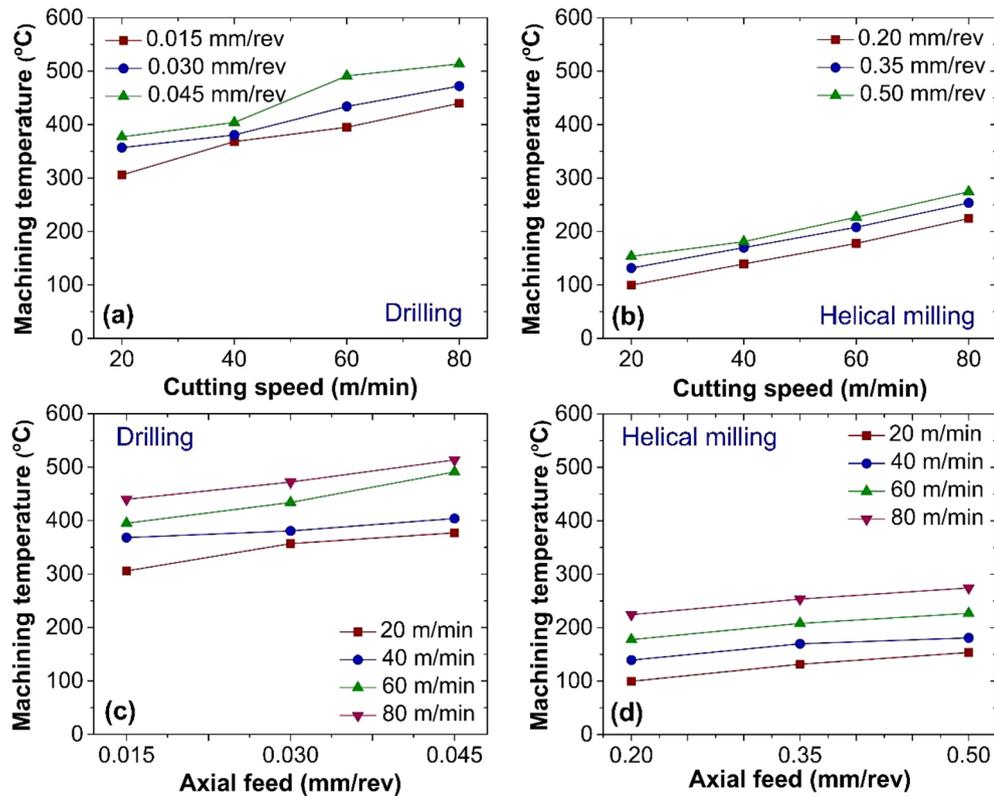


Fig. 10. (a) Machining temperature vs. cutting speed during drilling, (b) Machining temperature vs. cutting speed during helical milling, (c) Machining temperature vs. axial feed during drilling, (d) Machining temperature vs. axial feed during helical milling.

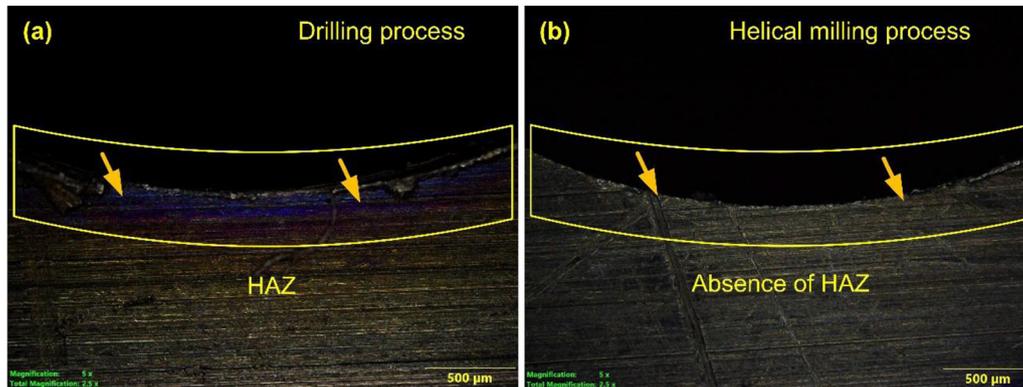


Fig. 11. (a) Workpiece discoloration due to high temperature during drilling, (b) Absence of workpiece discoloration during helical milling.

3.4 Analysis of hole diameter deviation

During hole making, maintaining a consistent diametrical accuracy is very crucial. Processing of undersized holes for riveting or screwing purposes can lead to unwanted stress and crack formation. In contrast, the oversized holes can cause loose assembly or even bearing failure. Therefore, the diameter of the drilled and milled holes is measured and analyzed. Figure 12 presents the variation in hole size from the nominal diameter value (6.80 mm) with the control factors during drilling and helical milling. The comparison reveals that the holes processed using conventional drilling are larger than those produced by helical milling.

To that effect, the deviation in entry and exit hole diameters (D_{en} and D_{ex}) with cutting speed and axial feed is analyzed. The variation in the hole diameter with the cutting speed is shown in Figure 12a. The drilled hole diameter nears the nominal diameter with the increase in cutting speed from 20 to 80 m/min. As the cutting speed increases, there is a rise in machining temperature. This softens the material, thereby facilitating smoother and stable cutting action with improved dimensional accuracy. Also, the change in axial feed influences the hole diameter, as seen from Figure 12b. The hole diameter increases as the axial feed increases from 0.015 to 0.045 mm/rev. The processing of holes with lower axial feed lowers the

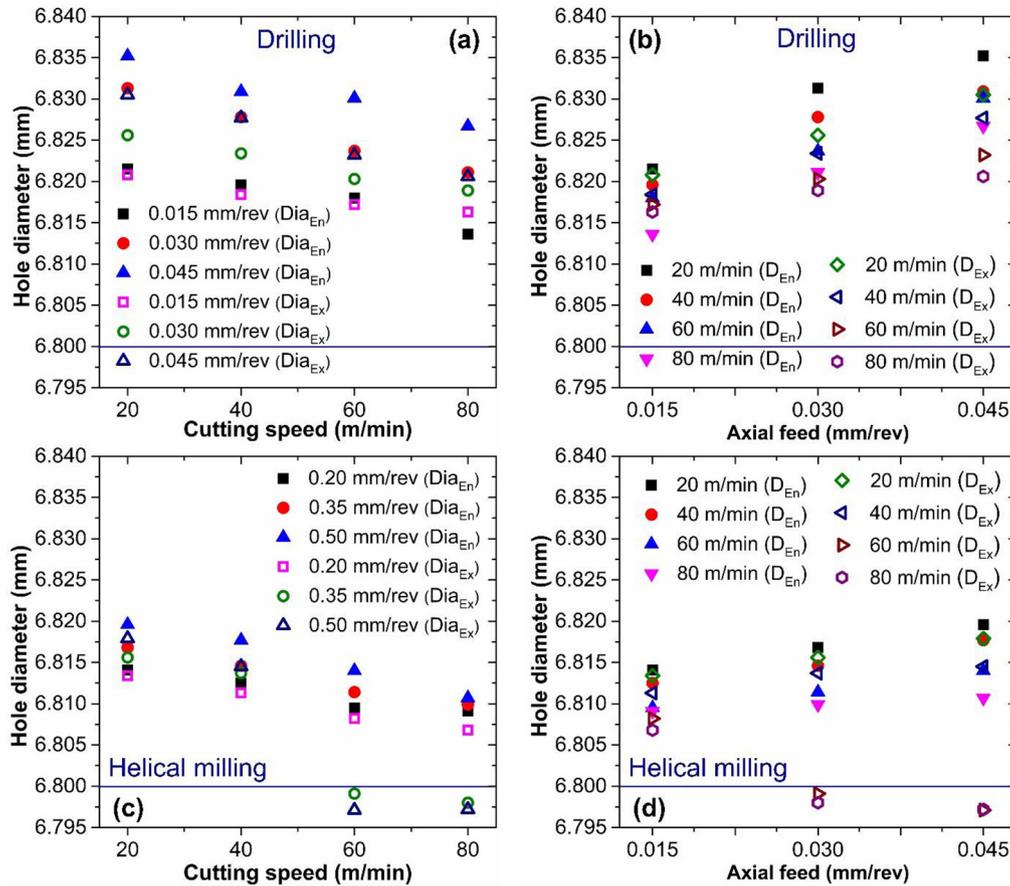


Fig. 12. (a) Diametrical deviation vs. cutting speed during drilling, (b) Diametrical deviation vs. axial feed during drilling, (c) Diametrical deviation vs. cutting speed during helical milling, (d) Diametrical deviation vs. axial feed during helical milling.

penetration rate of the tool. As a result, there is a reduction in chip thickness, thereby allowing stable cutting and reduced dimensional error. But with the increase in axial feed, self-induced vibration increases, causing the hole diameter to deviate from the nominal size [36]. Further, the examination of exit hole diameters reveals a similar trend, but the diametrical deviation is smaller than the entry hole. The larger deviation in the hole size at the entry is attributed to the high strength and hardness of the titanium alloy, which increases the prospect of drill wander leading to an oversized hole at the entry. The oversize of the drilled holes varied between $+18.0$ and $+35.2 \mu\text{m}$ at the entry and $+17.2$ to $+30.5 \mu\text{m}$ at the exit side. All the drilled holes showed poor dimensional accuracy, with hole diameter deviation exceeding the prescribed tolerance of H7 ($15 \mu\text{m}$ deviation) required in aerospace structures.

Figure 12c presents the deviation in hole size from the nominal diameter value (6.80 mm) with the cutting speed during the helical milling process. Cutting speed has a positive influence on the hole dimensional quality. The hole diameter deviation reduces with the increase in cutting speed from 20 to 80 m/min. The rise in the machining temperature with the cutting speed reduces the cutting force and improves dimensional accuracy. In contrast, the hole diameter is found to increase with the increase in the

axial feed from 0.2 to 0.5 mm/rev, as seen from Figure 12d. An increase in the undeformed chip thickness at elevated feed increases the thrust force, thereby inducing unstable machining and deteriorating the hole diametrical accuracy. Also, a similar trend is observed at the hole exit. However, the hole diameter at the entry is noted to be greater than the exit diameter. The larger deviation in the hole entry diameter can be attributed to the milling cutter's geometry and the machined material's high strength and hardness. Due to the absence of the chisel edges, during the initial plunge of the tool into the material, the sudden contact leads to impact load leading to tool deformation and vibration, resulting in a larger dimensional deviation at the entrance. Once the cutter enters the material, the chips are evacuated with ease due to the larger hole diameter. The material removal is also distributed between the end and side cutting edges, thus lowering the forces and aperture deviation at the hole exit. Based on the measurements, the oversize of the holes ranged between $+9.5$ and $+19.6 \mu\text{m}$ at the entry and $+11.3$ to $+17.9 \mu\text{m}$ at hole exit. As indicated, few of the processed holes lie within an H8 tolerance zone while most of the holes processed lie within the prescribed tolerance of H7 ($15 \mu\text{m}$ deviation), thus confirming the capability of helical milling to process holes as required by aerospace industries even under dry cutting condition.

3.5 Analysis of exit burrs

Burr formation during hole processing is undesirable because additional operations are needed for burr removal, which increases the production cost. Therefore, the holes processed using drilling and helical milling are examined for any burr formation at the hole exit. For similar productivity conditions, the size of burr in terms of burr height (b_h) and burr width (b_w) formed during the drilling process (see Fig. 13a and b) is larger in comparison to the helical milling process, as seen in Figure 13c and d. Since the formation of exit burr is noted during drilling and helical milling, the effect of cutting speed and feed on the size of the burr is further analyzed. Figure 14a shows the variation of burr thickness and burr height with cutting speed and axial feed during the drilling process. The size of the burr (width and height) increases with the increase in cutting speed. With the increase in cutting speed, the plastic deformation rate also increases. As the cutting tool reaches the exit side of the hole, the material which is in a

plastic state stretches before the material separates in the form of a burr cap. The extensive stretching results in a larger-sized burr at the hole exit.

Further analysis reveals the formation of large exit burrs at higher axial feed values. At higher axial feed, the amount of material being cut increases. The rise in the uncut material increases the deformation and thus the thrust force. During drilling, the magnitude of the thrust force increases at higher feed values due to the increase in uncut chip thickness. Under such conditions, the deformed material overflows at the hole exit, leaving traces of uncut material, thereby increasing the burr size [37,38].

As illustrated in Figure 14b, cutting parameters influence the size of the burr formed during the helical milling process. Machining at low cutting speed produces small-sized burrs. As the cutting speed increases, an increase in the formed burr's size at the hole exit edge is noted. The burr formation is attributed to plasticity induced due to the rise in machining temperature. As the end mill moves in a helical path at low feed conditions, both end and side edges in the cutting edges engage with the workpiece to shear the material. The distribution of the load between the two cutting edges reduces the thrust force. Also, as the end mill reaches the exit end of the hole, the end cutting edges of the tool push the material forward, while the side edges trim the material, thus reducing the size of the burr formed [18]. But as the axial feed increased, there is an increase in axial force (thrust force). Also, an increase in the amount of material being cut results in increased deformation and machining temperature. The induced plasticity under high-temperature conditions increases the burr size. Overall, it can be concluded that helical milling has a significant advantage over conventional drilling, considering the size of the generated burrs.

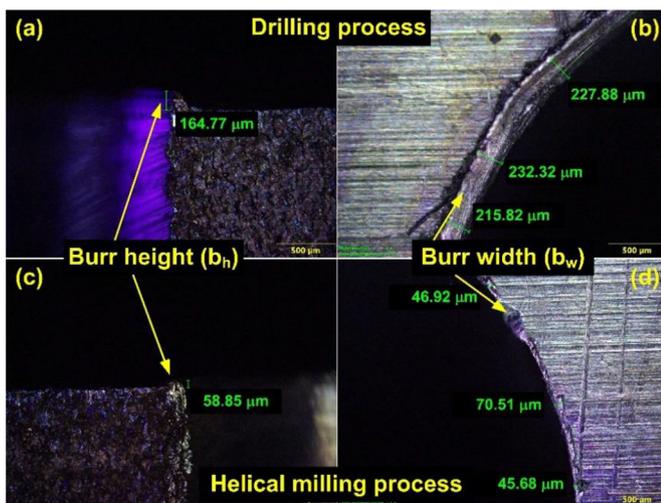


Fig. 13. (a) Burr height (b_h) during drilling, (b) Burr width (b_w) during drilling, (c) Burr height (b_h) during helical milling, (d) burr width (b_w) during helical milling.

4 Conclusions

A systematic study was carried out to compare the drilling and helical milling processes for hole making in Ti6Al4V titanium alloy. Five performance indicators, namely, thrust force, surface roughness, diametrical accuracy, machining temperature, and burr size, were considered, and the following conclusions were drawn:

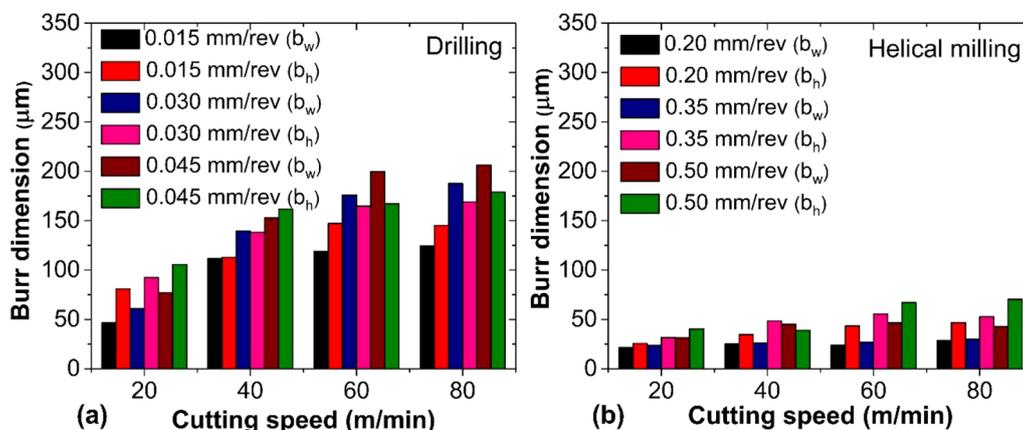


Fig. 14. Variation of burr height (b_h) and burr width (b_w) with control factors during (a) Drilling, (b) Helical milling.

- The thrust force magnitude was found to be 4–7 lower while processing holes with helical milling. The reduction in the force magnitude was attributed to the load distribution between the peripheral and axial cutting teeth. Further, the thrust force analysis revealed a reducing force trend with the cutting speed, while an increasing trend was noted with the increase in axial pitch.
- Even under dry cutting conditions, the surface finish obtained by helical milling was superior compared to the drilling process due to the generation of discontinuous chips and ease of evacuation at low cutting speed and feed conditions. But, helical milling at higher cutting speed and axial feed conditions resulted in the formation of chatter marks at the hole exit side due to the deformation of the slender end mill.
- A comparison of the machining temperature revealed the advantage of helical milling in terms of substantially lower values. Intermittent contact between the cutting tool and workpiece and ease of chip evacuation helped in lowering the machining temperature during helical milling. Further, the heat-affected zone (HAZ) formed due to the high machining temperature during the drilling process was conspicuously absent during the dry helical milling process.
- The hole diameter analysis showed that the dimensional deviation was larger at the hole entrance than at the hole exit for both the machining processes. But the helical milling process could produce H7 quality holes at high cutting speed and lower axial feed conditions.
- On comparing the two processes, the helical milling process presented a significant advantage over the drilling process, considering the reduction in the size of the burr formed at the hole exit.

Overall, it can be concluded that helical milling has a significant advantage over conventional drilling due to its capability to produce quality holes under dry machining conditions. However, tool wear is still a significant issue during helical milling of difficult-to-machine material like titanium alloy due to the utilization of peripheral cutting edge and frontal cutting edge for material shearing. Also, the microstructural changes in the work material due to high machining temperature are undesirable. Therefore, an investigation is warranted to analyze the tool wear and microstructural changes due to high machining temperature to further ascertain the advantages of the helical milling process.

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