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Drill Life Optimisation when Drilling Ti-6Al-4V with HSS Drills

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Abstract

Relatively low machinability of titanium and its alloys is caused mainly by their poor thermal conductivity, low modulus of elasticity, chemical reactivity with cutting tool materials at high temperatures and work hardening characteristics that produce high chip loads near the tool cutting edge of the tools. However, the widespread use of titanium and its alloys for critical components in many applications, has attracted significant attention for investigations on machinability resulting in a number of recommendations.

In many instances, particularly for small production runs of deep-hole drilling in titanium alloy components, drilling operations are carried out by using HSS drills. Not much literature is available concerning this aspect of drilling. This paper presents an investigation wherein cutting forces, acoustic emissions and chip formation were examined during deep-hole drilling of Ti-6Al-4V at various cutting speeds and feed rates and optimum drilling parameters were determined. Then a CNC program that incorporated the optimum cutting speed and feed parameters, along with a series of chip breaker and full relief steps, was developed. The CNC program was observed to provide a trouble-free deep drilling operation on Ti-6Al-4V bars with high-speed steel drills.

1. Introduction

The unique properties of Ti-6Al-4V such as high strength to weight ratio, low thermal conductivity, good corrosion and fracture resistance, have made it an excellent choice for components used in industrial, chemical, surgical, marine and aerospace applications. However, several of these properties are also the reason titanium and its alloys are considered materials that are difficult to machine. Problems during drilling on these materials arise mainly due to generation of high chip loads near the cutting edge of the tools and poor heat conduction of the work piece which results in excessive chip packing and welding to the cutting edge of the drill.

In recent times, significant research effort has been directed for investigation of the machinability of titanium and its alloys. The research has mainly focused on chip formation mechanics, tool wear, machinability, component quality and recommendations on cutting parameters for machining these materials. Although pioneering work on machining titanium alloys was done by MC Shaw et al (1), the fundamental research on chip formation mechanism during machining of these alloys was carried out by Komanduri, Turkovich and Brown (2-4). A catastrophic shear-failed chip formation which is mainly independent of cutting speed, was observed by them. Zlatin and Field (5) commented on the unique characteristics that make machining operations of titanium alloys difficult. They also recommended a range of cutting speeds and feed rates for drilling Ti-6Al-4V with HSS drills. Around the same time Hartung and Kramer (6) investigated the tool wear behavior in machining titanium alloys with tools made of different materials, and proposed a model explaining the mechanism of wear. Bhauunik et al (7) investigated the failure of conventional tool materials such as HSS and cemented carbides due to high temperature generated and titanium's chemical affinity. They also observed that wurtzite boron nitride based cutting tools provided better results compared to HSS and carbide tools.

Several aspects pertaining to drilling of titanium alloys have also been investigated by a number of researchers. Novel cutting strategies such as low frequency vibratory drilling with intermittently accelerated feed have been employed by Sakurai et al (8-10). These techniques were observed to have reduced chip-clogging, better heat dispersion to exterior and improved access of cutting fluid to the drill cutting edges resulting in significantly higher tool life compared to conventional drilling. Arai and Ogawa (11) examined the effects of high pressure coolant supply through the drill in drilling of titanium alloys. The technique allowed deeper holes to be drilled due to smooth chip ejection, effective cooling of cutting edges and reduced tool wear. Influence of drill geometry and cutting process parameters on burr formation and hole quality have been investigated by Dornfeld et al (12) and Dechow (13) respectively. However, both of these studies employed 10mm diameter drills for drilling 6mm deep holes and reported better results with higher point and helix angles. Other studies on drilling of titanium alloys include influence of hard coatings on drill life and power consumption (14) and prediction of drill wear employing measured cutting forces (15). Significant effort has been directed towards research on machining and drilling titanium alloys. However, apart from feed and speed adjustments recommended by Metcut (16), little or no practical set of parameters for deep drilling of Ti-6Al-4V with HSS drills is available. The present research was therefore undertaken to fill this gap and to cater for the needs of small industries who, due to financial constraints, use HSS drills for drilling deep holes in titanium alloy components requiring short production runs.

2. Experimental Setup

The drilling operation optimization tests were conducted on a three axis Zenford Ziegler CNC Machining Centre. A schematic arrangement of the experimental setup is presented in Figure 1. A specially designed fixture was employed to hold round Ti-6Al-4V work specimens having 25.4mm diameter and 100 mm length. This fixture was mounted on a base plate which in turn, was fixed to a Kistler 9207 drilling dynamometer bolted to the milling machine table via a 25mm thick plate. Sutton Tools Deep Hole Jobber HSS Co TiNite® coated drills with 135° point angle and 40° helix angle were employed for drilling experiments. The thrust force, torque and acoustic emission signals from the drilling operation were collected and digitized synchronously through an A/D converter and stored on the hard disk of an IBM compatible computer for analysis at a later stage. The drilling parameters used in the experimentation were selected from the previous research and are detailed in Table 1.
Cuttinl! Conditions

HSS drill diameter 10mm
Cutting speed 6-12mm/min
Feed 0.10 – 0.22mm/rev
Point angle 135°
Helix angle 40°

Table 1. Drilling parameters employed for experimentation

<table>
<thead>
<tr>
<th>Cutting Conditions</th>
<th>Range</th>
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<tr>
<td>HSS drill diameter</td>
<td>10mm</td>
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<tr>
<td>Cutting speed</td>
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<tr>
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<td>135°</td>
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<tr>
<td>Helix angle</td>
<td>40°</td>
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3. Experimental Procedure

In order to optimize the drill life, a systematic procedure was followed to narrow down the range of cutting parameters and reduce chip-clogging during drilling operations. Initially, a wide range of drilling parameters (Table 1) was obtained from the machining industry recommendations and previous research work in this area. Examining the torque and thrust generated during drilling operation on Ti-6Al-4V rods with a number of cutting parameters, the range was narrowed down to one set of cutting conditions, the use of which caused no increase in thrust or torque on the drill for a significant hole depth (40mm). In many of these drilling experiments, lack of smooth chip flow (chip packing) and chip congestion was found to be a major problem. In the subsequent tests therefore, effort was focused on the development of a drilling procedure and a CNC program which allowed frequent breaking and dislodgment of chips from the drill flutes.

4. Results and Discussion

4.1 Optimum Cutting Speed and Feed Rate

In order to determine an optimum cutting speed and feed for deep hole drilling on Ti-6Al-4V with HSS 10mm diameter drills, a number of drilling operations were carried out with several different cutting parameters. Thrust force, drilling torque and acoustic emissions (AE rms) generated during the drilling operation were measured for all these tests.

Figures 2 and 3 show the thrust force and torque on the drill when drilling with a cutting speed of 6m/min and feed rates ranging form 0.10 to 0.22mm/rev. An examination of the thrust forces indicates that the feed rate of 0.10mm/rev generates the lowest forces on the drill. However, after drilling a depth of 40mm with this feed, there was extreme wear on the drill which rendered it unsuitable for further drilling. The drill was reground and shortened by 10mm during resharpening. After reaching peak values of about 2.4kN, the thrust forces stabilize, then fall a little and remain stable up to about 30mm hole depth. However, after that the forces for 0.14mm/rev and 0.22mm/rev feed rates appear to increase steeply. Unlike thrust, larger torque is generated on the drill by higher feed rates (Figure3). The figures also highlight that after a hole depth of about 8mm, the magnitude of the torque increased significantly over the full depth of drilling, and consistent with thrust forces, steep increases in torque were observed for feeds of 0.14 and 0.22 mm/rev, after 30mm hole depth. An examination of the chips generated in these tests indicated that at lower feeds, the chips become knotted resulting in blockage of flutes, while higher feed rates produce uniform and stronger chips which have less chance of folding back and blocking the drill flutes (Figure 4). The extreme flank wear, blockage of drill flutes and similar observations of previous researchers for low feed rates, suggested that 0.10 mm/rev feed rate is not suitable for high machinability and hence was not used in future tests.

Figure 1. Schematic arrangement of the experimental setup
The thrust and torque variations in drilling with a cutting speed of 9 m/min and feeds of 0.14, 0.18 and 0.22 mm/rev are presented in Figures 5 and 6. An examination of these figures clearly indicates that a cutting speed of 9 m/min and a feed rate of 0.14 mm/rev have optimum results of all these tests. As the feed of 0.14 mm/rev was observed to provide a fairly constant torque (4-5 Nm) and a thrust force, which does not exceed 2 kN over the full depth of the hole, hence in future tests, it was decided to use this feed rate with varying cutting speeds.

In order to narrow down the range of cutting speeds further, it was decided to do two more drilling tests with cutting speeds of 10 and 12 m/min and a feed of 0.14 mm/rev. The thrust force and torque on the drill in these tests are presented in Figures 7 and 8.
then progressively rises to about 18Nm. The stability of the thrust force and torque to 9m/minute (Figures 5 and 6). This observation is reinforced by recent research (17).

An examination of these figures indicates that the thrust forces on the drill in both cases settle down around 2kN and 1.8 kN respectively. However, the torque on the drill when drilling with a speed of 12m/minute, rises very steeply in the first 10mm of the hole depth drilled and then settles out at about 20Nm. When the cutting speed of the drill is reduced to 10m/minute, not only is the thrust force slightly lower (17-18kN) but the torque remains fairly low at 5Nm till a hole depth of about 15mm and then progressively rises to about 18Nm. The stability of the thrust force and torque on drill is significantly better when the cutting speed of the drill is further reduced to 9m/minute (Figures 5 and 6). This observation is reinforced by recent research (17) wherein the reduction of cutting speed from 20 to 10m/minute was found to significantly reduce the adhesion of titanium chips on the cutting edges of HSS drills, resulting in lower wear and greater stability of cutting forces.

The drilling tests conducted and observations of drill wear, indicate that a cutting speed of 9m/minute and a feed of 0.14mm/rev is the optimum setting for drilling Ti-6Al-4V using 10mm diameter HSSCo TiNite® drills.

5. Development of an Optimum CNC Program

The cutting speeds and feeds in drilling Ti-6Al-4V influence the chip formation. However, it is very important that the chips formed during drilling be broken fairly frequently, so that they can exit smoothly outside the hole/work piece and do not cause any clogging in the flutes and blockage of the fluid access to the drill cutting edge. The aim of this part of the experimentation was to determine the optimum hole depth and the number of times the drill needs to be relieved, either all the way out of the hole or just back from the cutting face to break the chips. The analysis relied mainly on the thrust and torque measurements and visual observation of tool wear as well as chip formation. Using this strategy, a number of CNC drilling programs were developed and employed for drilling tests.

The first test for this part of the experimentation involved a two-stage drilling operation wherein the drill was fully retracted after drilling to a depth of 40mm and then immediately drilling to a depth of 70mm. A sharp rise in torque and extreme flank wear on the drill were observed. The severe wear made the drill unusable for further drilling. It appears that the tightly knotted chips formed not only blocked the passage of coolant to the drill cutting edge, but they also caused significant friction heat due to rubbing on the hole sides. In further tests, cues were taken from the previous tests wherein it was observed that the chip blockage starts to occur at about 20mm hole depth, resulting in an increase in torque. The depth at which the drill was first fully retracted was progressively decreased, and the frequency of further full or partial retractions of the drill was increased. Torque and thrust on the drill during drilling with three such typical programs, are presented in Figures 9, 12 and 13.

An examination of Figure 9 clearly indicates that after the first full retraction of the drill, the torque grew slowly up to 50mm hole depth and thereafter both the thrust force and torque rose steeply from 2.3kN and 7.5Nm to 3.5kN and 20 Nm respectively. They continued to remain high and further increased even after drill retraction at 65mm depth and eventual breakage of the drill. This suggests that the damage to the cutting edges was done in the 45mm to 60mm depth range and thereafter the drill condition rapidly deteriorated until seizure and breakage.

The sequence of drill feeds including full or partial retraction of drill during two drilling tests is shown in Figures 10 and 11. The respective thrust force and torque variation on the drill during these tests are presented in Figures 12 and 13. An examination of these figures indicates that the torque and thrust forces build-up has been significantly restricted to small increases at deeper hole depths. However, extra two partial retractions of the drill in chip breaker sequence 2 compared to chip breaker sequence 1, result in a better stability of thrust force and torque on the drill as well as an occurrence of minor wear only in the first drilling cycle.
Figure 9. Thrust and torque variation for 3-step drilling process (V=9m/min)

Figure 10. 1st Chip-breaker sequence

Figure 11. 2nd Chip-breaker sequence

Figure 12. Thrust and torque variation for 1st chip-breaker program (V=9m/min)
6. Conclusions

The high modulus and low thermal conductivity of Ti-6Al-4V result in poor chip formation causing significant clogging of flutes during drilling operations employing HSS drills. Low heat transfer resulting in chip material welding to the drill cutting edge coupled with excessive chip packing, can cause severe damage to the drill and subsequent seizure or breakage. This research has developed a new technique, which allows a reduction in chip clogging and facilitates drilling of deep holes in Ti-6Al-4V using HSS drills.

The conclusions of this research can be summarized as follows:

- When drilling Ti-6Al-4V alloy with HSS long series drills of 10mm diameter, a feed of 0.14mm/rev and a cutting speed of 9m/min were observed to give smooth chip formation and flow through the drill flutes.
- A strategy involving regular full retractions of the drill and a few partial retractions allowing chip breaking has been found to successfully drill deep holes (7:1).
- A CNC program, which incorporates this strategy as well as optimum speed and feed parameters, has also been developed. This program should enable machinists to deep drill Ti-6Al-4V alloy economically without fear of drill seizure.

7. References