Starting Recommendations for Drilling Austempered Ductile Iron (ADI)

A series of experiments were conducted to evaluate the machinability of ADI for drilling applications. This drilling study was completed on Grade 1 ADI and Grade 3 ADI. 100-70-03 ductile iron (as-cast material) was used as the reference material. Note that the starting drilling parameters for Grade 2 ADI are a result of an extrapolation based on prior face milling experiments. When drilling Grade 2 ADI, a slower cutting speed (approximately 5% slower) than that used for Grade 1 ADI should be utilized. The recommended drilling parameters for 3 grades of ADI with expected tool life of 20 minutes are summarized in **Table 1**.

Table 1: Recommended initial drilling parameters for ADI

Material	Feed (in/rev)	Cutting speed (ft/min)
A536 60-40-18	0.009 0.011 0.017	560 – 425 – 295
Grade 1 ADI		***520 – 420 – 265***
Grade 2 ADI[2]		***470 – 380 – 240***
A536 80-55-06		490 – 360 – 230
A536 100-70-03		
A536 120-90-02	0.006 0.009 0.013	425 – 330 – 230
Grade 3 ADI		***300 – 140***

Material	Feed (mm/rev)	Cutting speed (m/min)
A536 60-40-18	0.22 **0.29** 0.43	170 – 130 – 90
Grade 1 ADI		***160 – 120 – 80***
Grade 2 ADI[2]		***145 – 115 – 70***
A536 80-55-06		150 – 110 – 70
A536 100-70-03		
A536 120-90-02	0.15 **0.24** 0.33	130 – 100 – 70
Grade 3 ADI		***80 – 40***

[1]Recommendations are based on the use of SECO CrownLoc Plus SD403-12.00/12.49-38-16R7 and QuakerCool 7020-CG.
[2]Grade 2 ADI results are extrapolated based on prior face milling experiments because the austenite/ferrite ratio was nearly the same for the Grade 2 ADI and Grade 1 ADI produced for this study.

Research Study Details

The drilling experiments were carried out using a HAAS VF-3 vertical CNC Mill with thru-spindle coolant capability. The 305x151x25 mm plate workpiece was clamped on all four corners to allow for through-hole drilling. The setup for the drilling experiments is shown in **Figure 1**. The casting scale of the workpiece was removed prior to testing to minimize variation. The tool life was defined as the time when the drill fractured.

All three materials (100-70-03 DI, Grade 1 ADI, and Grade 3 ADI) were initially drilled using the same drilling parameters, which was the recommended cutting speed for drilling 100-70-03 DI using a SECO SD403 CrownLoc Plus in order to establish a starting point for testing. This result is summarized in **Figure 2**.

Figure 1: The HAAS VF-3 drilling workpiece is shown.

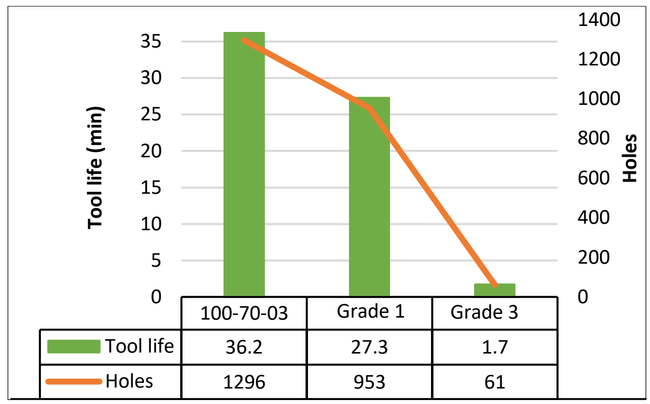

Figure 2: The preliminary results for the drilling experiments are shown.

When these materials were drilled at a cutting speed of 360 ft/min and a feed rate of 0.011 in/rev, the tool used to drill Grade 1 ADI still performed well (27 minutes) while the drill only lasted for 2 minutes when machining Grade 3 ADI. Due to this result, the cutting speed and/or feed rate used in the subsequent tests were increased for Grade 1 ADI and decreased for Grade 3 ADI. The drilling parameters used in this experiment are shown in **Table 2**.

Table 2: Drilling parameters used for Grade 1 ADI and Grade 3 ADI.

Grade 1 ADI			*Grade 3 ADI*		
Insert	**V (ft/min)**	**f (in/rev)**	**Insert**	**V (ft/min)**	**f (in/rev)**
1	360	0.011	1	360	0.011
2	490	0.011	2	230	0.011
3	490	0.017	3	230	0.009

Tool Life

The relationship between cutting speed, feed rate and tool life was established in the form of the modified Taylor tool life equation. The modified Taylor tool life equations for Grade 1 ADI and Grade 3 ADI are shown in **Table 3.** These equations can be used to approximate the starting cutting speed for a desirable tool life depending on different machine shops' preferences (i.e. productivity vs. cost). The recommended drilling parameters shown in **Table 4,** are generated based on various expected tool life.

Table 3: Taylor tool life equations for Grade 1 and Grade 3 ADI.

Material	Taylor Tool Life Equation
V (ft/min) – T (min) – f (in/rev)	
Grade 1 ADI	$V\ T^{0.38}\ f^{1.04} = 11.9$
Grade 3 ADI	$V\ T^{0.58}\ f^{1.78} = 0.19$
V (m/min) – T (min) – f (mm/rev)	
Grade 1 ADI	$V\ T^{0.38}\ f^{1.05} = 106$
Grade 3 ADI	$V\ T^{0.58}\ f^{1.72} = 18$

The wear mechanisms observed in this study confirm the wear mechanisms previously described by Meena [1]. At a low cutting speed and a low feed rate, adhesion wear causing built-up-edge was mainly responsible for the tool deterioration. The built-up-edge formation started to diminish with increasing drilling speeds and feed rates, but chipping started to take place. At a medium cutting speed and a low feed rate, drills experienced both adhesion and diffusion wear, which resulted in crater wear. The diffusion wear decreased with increased feed rate. Meena also observed that at a high drilling speed and a high feed rate, cracks might occur due to high compressive stress and temperature at the cutting edge [1]. The use of coolant and particularly through-spindle-coolant minimized the flank and crater wear during the drilling of ADI.

Chip Formation

Cone-shaped chips with "closeness" reflect an appropriate selection of drilling parameters. Too low cutting speeds results in needle-shaped chips while fragmented chips are obtained when excessive cutting speeds are used. The spacing of these chip segments will increase with an increase in feed rate.

Figure 3: Chips formed when drilling Grade 3 ADI at low speed (left) and high speed (right).

Surface Finish

The selection of range of drilling speed is critical before adjusting the drilling feed rate. Drilling speeds must be high enough to diminish the effect of built-up-edge, which results in a poor surface finish. After a range of appropriate cutting speeds is established, the surface finish can be improved by reducing the feed rates and the use of appropriate coolant. The surface finish increases somewhat with increasing tool wear. A surface roughness of 20 µin (0.51 µm) can be obtained when drilling ADI.

The resulting ADI drilled holes are expected to be 0.001-0.003 in. (0.02-0.08 mm) larger than the nominal drill diameter. The deviation from the nominal value decreases as the tool wears out; however, excessive wear will cause an increase in hole diameter. High drilling speeds and feed rates seem to increase the hole diameter slightly due to increased cutting force and vibration.

In order to minimize the burr height, a low drilling speed and feed rate are desirable. Burr height increases as the tool wears out. Inappropriate selection of drilling parameters will result in excessive burr heights. In the case of the through-hole drilling, the burr height at drill exit will be greater than that measured at drill entrance.

Cutting Forces

Thrust force and torque are expected to increase with increasing cutting speeds and feed rates. However, the specific cutting energy was observed to decrease with an increase in feed rate and a decrease in cutting speed due to higher mechanical and thermal loads on the drill's cutting edge [2]. The use of lubricants during drilling is essential because a lower cutting force [3] and a longer tool life [4] have been observed when drilling with cutting fluids. In addition to coolant, chamfered cutting edge corners have also been recommended to prolong the tool life during the drilling of ADI [5].

References

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Table 4: Recommended initial ADI drilling parameters for various expected tool life.

Tool Life (min)	**Drilling speed (ft/min) – d = 1 in** *Drilling speed (ft/min) – d = 25 mm*							
	Grade 1 ADI			**Grade 2 ADI**			**Grade 3 ADI**	
T = 15 min	**0.009 in/rev** *0.23 mm/rev*	**0.011 in/rev** *0.29 mm/rev*	**0.017 in/rev** *0.43 mm/rev*	**0.009 in/rev** *0.23 mm/rev*	**0.011 in/rev** *0.29 mm/rev*	**0.017 in/rev** *0.43 mm/rev*	**0.006 in/rev** *0.15 mm/rev*	**0.009 in/rev** *0.23 mm/rev*
3T	**380** *115*	**310** *95*	**195** *60*	**340** *105*	**280** *85*	**175** *55*	**170** *50*	**85** *25*
2T	**445** *135*	**360** *110*	**230** *70*	**400** *120*	**325** *100*	**205** *65*	**215** 65	**105** *20*
T + 5	**520** *160*	**420** *130*	**265** *80*	**470** *145*	**380** *115*	**240** *70*	**270** *80*	**135** *40*
T	**580** *175*	**470** *145*	**300** *90*	**520** *155*	**425** *130*	**270** *80*	**320** *95*	**155** *50*
T – 5	**680** *205*	**550** *165*	**350** *105*	**610** *185*	**495** 150	**315** *95*	**405** *125*	**200** *60*