Starting Recommendations for Milling Austempered Ductile Iron (ADI)

A series of face milling experiments were conducted to evaluate the machinability of ADI. The results of these experiments were expected to show how different grades of ADI (Grade 1 ADI, Grade 2 ADI, and Grade 3 ADI) affect the milling performance. AISI 4340 with hardness similar to that of Grade 2 ADI was used as the reference material. The effects of different milling parameters on the tool life when machining ADI were analyzed to provide starting recommendations for milling ADI. The recommended milling parameters for ADI (**Table 1**) were generated using the modified Taylor tool life equations with expected tool life of 20 minutes and depth of cut of 0.039 in (1 mm). Note that the recommended cutting speed for Grade 2 ADI was interpolated. In addition, with increased feed rate, the range of recommended cutting speed became wider. This indicates that more trial and error should be done when a higher feed rate is to be used.

Table 1: Recommended initial milling parameters for different grades of ADI.

	Feed (in/tooth) ***(mm/tooth)***			
	0.003 *0.08*	0.006 *0.15*	0.010 *0.25*	0.014 *0.36*
Material	**Cutting speed (ft/min)** ***(m/min)***			
A536 60-40-18		870 *265*	740 *225*	660 *200*
A536 80-55-06		760 *230*	650 *195*	580 *175*
Grade 1 ADI	**820** ***250***	**730** ***225***	**675** ***205***	**640** ***190***
Grade 2 ADI	**720** ***220***	**690** ***200***	**645** ***190***	**615** ***180***
A536 100-70-03		640 *195*	550 *165*	490 *150*
Grade 3 ADI	**550** ***165***	**535** ***163***	**525** ***160***	
A536 120-90-02		530 *162*	455 *140*	

*Recommendations are based on the use of SECO Double Octomill 220.48-09S R220.48-03.00-09-06SA as the tool holder, SECO ONMU090520ANTN-M14 MK2050 as the inserts and QuakerCool 7020-CG for the coolant.

Research Study Details

The face milling experiments (**Figure 1)** were carried out using 3-insert configuration. The experiments were performed on a HAAS VF-2 vertical CNC Mill with the use of a large modular vise to support workpiece (305x151x25 mm). The casting scale of the workpiece was removed prior to testing because the scale is not of main interest.

The tool life experiments were conducted according to ISO 8688. Five cutting speed configurations with a constant feed rate of 0.003 in/tooth and depth of cut of 0.039 in. were investigated per work material with three replications per condition to establish the relationship between cutting speed and tool life. Grade 1 ADI and Grade 2 ADI were milled at cutting speeds ranging from 787 to 1575 ft/min, while Grade 3 ADI was milled at a lower range of cutting speed (394 – 1181 ft/min). AISI 4340, however, was tested only at a cutting speed of 1181 and 1575 ft/min. Additional testing with different feed rates and depth of cuts was performed to analyze the effects of these cutting parameters on tool life.

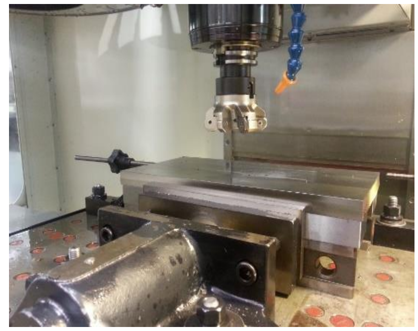

Figure 1: The setup for the milling experiment is shown.

Tool Life

A linear relationship between the tool life and cutting speed, also called Taylor tool life equation, was established based on the experimental data. Taylor tool life equations for different grades of ADI and AISI 4340 are derived from the linear regression model are presented in **Table 2**. These equations can be used to approximate the starting cutting speed for a desirable tool life. The importance of establishing this relationship is the ability to fulfill the different preferences from machine shops (i.e. productivity vs. cost).

Table 2: Taylor tool life equations for ADI and AISI 4340.

Material	Taylor Tool Life Equation
V (ft/min) – T (min)	
Grade 1 ADI	$V\,T^{0.40} = 2681$
Grade 2 ADI	$V\,T^{0.37} = 2246$
Grade 3 ADI	$V\,T^{0.36} = 1627$
AISI 4340	$V\,T^{0.25} = 2119$

Instead of categorizing the data into three groups (Grade 1 ADI, Grade 2 ADI and Grade 3 ADI), the data was "pooled" and analyzed all at once. By "pooling" the data, one combined regression equation could be generated for three grades of ADI instead of three equations by treating the grades of ADI as binary predictor variables. Three grades of ADI were coded as:

If material = Grade 1 ADI, then Grade_1 = 1 and Grade_2 = 0
If material = Grade 2 ADI, then Grade_1 = 0 and Grade_2 = 1
If material = Grade 3 ADI, then Grade_1 = 0 and Grade_2 = 0

The regression equation which can be used to describe the effects of cutting speed and ADI grade on tool life was found to be:

$$\ln(T) = 9.5 - 2.62 \ln(V) + 1.10\,\text{Grade\_1} + 0.73\,\text{Grade\_2}$$

for *T in min* and *V in ft/min*

Furthermore, Modified Taylor tool life equations (**Table 3**) were derived from multiple regression analysis, involving not only milling speeds but also feed rates and depths of cut. The study showed that, by using a cutting speed of 984 ft/min, feed rate of 0.003 in/tooth and increasing the depth of cut to 0.055 in, the tool life increased without sacrificing the MRR. This observation is in agreement with the recommendation on machining ADI at a deeper cut. Although this behavior is desirable, it should be noted that this was observed on the testing range of depth of cut of 0.039-0.055 in. The effect of depth of cut on tool life outside this range should be further validated.

Table 3: Modified Taylor tool life equations for ADI.

Material	Modified Taylor Tool Life Equation
V (ft/min) – T (min) – f (in./rev) – d (in.)	
Grade 1 ADI	$V\ T^{0.40} f^{0.16} d^{-0.08} = 1680$
Grade 3 ADI	$V\ T^{0.38} f^{0.04} d^{-0.11} = 2145$

Milling parameters with coated carbide and coolant recommended for milling ADI for various expected tool life are shown in **Table 4**. It must be noted that 1370 m/min and 1240 m/min should be the maximum limit of cutting speeds to mill Grade 1 ADI and Grade 2 ADI (for a minimum expected tool life of 5 min). A cutting speed of 390 m/min and 910 m/min are set to be the lower and upper boundary of cutting speeds used to mill Grade 3 ADI.

Chip Formation

Continuous, less serrated and wider chips are desirable when machining ADI. This chip formation is promoted by using low milling speeds and feed rates with deeper cuts. Increased cutting speeds and feed rates resulted in shorter, flatter, and more serrated chips. Deeper cuts tend to increase the chip width. Heat carried out by the chips was reflected in the gold color on the continuous (longer) and less serrated chips.

Surface Finish

Surface roughness Ra measurements between 7.8–31 µm were obtained when milling three grades ADI using a cutting speed of 787-1575 ft/min for Grade 1 ADI and 394-1181 ft/min for Grade 3 ADI with a feed rate of 0.009-0.012 in/rev and a depth of cut of 0.039-0.055 in. These Ra values were lower than the theoretical value of 40 µin stated by Seco Tools for the tool used in this study. However, cutting speeds of 390 m/min and 1180 m/min must be excluded when milling Grade 3 ADI due to early catastrophic failure at the low end and the slightly higher surface roughness along with low tool life at the high end. While it was minimal, lower feed rates or deeper cuts can be expected to improve the surface finish of ADI.

Cutting Forces

Increasing the chip load generally resulted in an increase in resultant cutting forces and a decrease in specific cutting stiffness for all materials. Slightly lower cutting forces were observed when machining Grade 3 ADI at a lower chip load (0.002-0.004 in/tooth) due to minimum plastic deformation. The specific cutting forces for ADI are in the range of specific cutting force k_{c1} for ISO-H (hardened steel). The specific cutting stiffness for ADI was greater at a low chip load and was only slightly higher than 100-70-03 ductile iron at high chip load. Savkovic [1] also found that the maximum cutting forces for ADI were 25% higher than those required for machining as-cast material using the same cutting parameters.

Cutting Tool and Conditions

A coated carbide tool is recommended instead of an uncoated carbide tool when milling ADI [2]. Furthermore, the use of positive rake angle cutting tool with a light-chamfered cutting edges should also be considered to prevent premature tool failure [3].

The role of coolant to improve tool life when milling ADI is still an open question. Past studies have shown that longer tool life was obtained when milling lower strength ADI grades in the dry condition [4], [3]. Different wear mechanisms when milling ADI in wet (abrasive wear) and dry (notch wear) cutting condition were believed to be the reason for this observed behavior [4]. Moreover, the use of coolant also intensified the effects of thermal fatigue due to cyclic heating and cooling [3].

References

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

Tool Life (min) T = 15 min	**Cutting speed (ft/min) – f = 0.003 in/tooth** *Cutting speed (m/min) – f = 0.08 mm/tooth*					
	Grade 1 ADI		**Grade 2 ADI**		**Grade 3 ADI**	
	d = 0.04 in *1.0 mm*	**d = 0.06 in** *1.5 mm*	**d = 0.04 in** *1.0 mm*	**d = 0.06 in** *1.5 mm*	**d = 0.04 in** *1.0 mm*	**d = 0.06 in** *1.5 mm*
2T	**700** *210*	**720** *220*	**610** *185*	**630** *190*	**470** *140*	**500** *150*
T + 5	**820** *250*	**850** *260*	**720** *220*	**740** *225*	**550** *165*	**580** *175*
T	**900** *275*	**950** *290*	**810** *245*	**830** *250*	**620** *190*	**650** *200*
T – 5	**1080** *330*	**1120** *340*	**950** *290*	**980** *300*	**720** *220*	**760** *230*
0.5T	**1220** *370*	**1260** *385*	**1070** *325*	**1100** *335*	**800** *245*	**850** *260*