Machinability of Solution Strengthened Ferritic Ductile Iron

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ABSTRACT

Solution strengthened ferritic ductile iron is a grade of ductile iron where the ferritic matrix is solution strengthened by silicon. The addition of silicon results in a combination of higher mechanical properties and higher elongation as compared to standard grades of ductile iron. Some research suggests silicon solution strengthened ferritic ductile iron (SSFDI) grades can result in a 10-50% machining cost savings compared to conventional grades. Although these grades can result in lower machining costs, some grades have an increased base cost in the raw material form. For example, 500-14 SSFDI and 600-10 SSFDI ductile iron grades can be 1% to 4% higher in base casting costs over comparable conventional grades. An overall lack of machining knowledge has impeded the growth of 500-14 SSFDI and 600-10 SSFDI in North American markets, due to machining costs being kept at conventional grade speeds and feeds.

Keywords: solution strengthened ferritic ductile iron, SSFDI, base cost, machining cost, machinability

INTRODUCTION

To evaluate the machinability of SSFDI grades a drilling, milling, and rough turning machinability test was carried out to determine the tool life and cutting forces between two grades of SSFDI with two comparable grades of conventional ductile iron. The comparable grades were grouped based on yield strength criteria, since most designers will ultimately select a suitable material for its mechanical properties.

Three surface cutting speeds, two cutting feeds rates, and a consistent depth of cut were used for the test matrix. It was shown that, across the board, the overall tool life for drilling, milling, and turning of SSFDI increases the expected tool life even with similar cutting forces. However, an unexpected yet fascinating observation with milling SSFDI showed that it performed exceptionally well, to the point of being able to push the surface cutting speed significantly above the maximum recommended range. This research compiled the given yield strengths of materials and grouped them to perform similar surface speeds across alike feed rates and compared the machining results.

Machinability is a term used to describe how easily a material can be cut or machined with a cutting tool. A material that is characterized with a good machinability will be easier to cut without damaging the cutting tool, consume less power to machine, and produce a better surface finish, whereas a material with a poor machinability will be hard to cut, generate a greater amount of heat transferred to the tool and potentially result in premature cutting tool wear and/or failure.

One factor of great significance in metal cutting is tool wear. The usable life of a cutting tool used in machining plays an important role in overall machining costs. The International Organization for Standardization (ISO) 3685 specifies the recommended procedures for tool-life testing steel and cast-iron workpieces with high-speed steel, sintered carbide, and ceramics for single-point turning tools in a laboratory setting or in production.[1]

Because there is a lack of machining knowledge for some of the SSFDI materials, a machinability test was conducted between like yield strength materials. Designers typically select materials based upon mechanical strength properties, so evaluating the machinability of similar yield strength materials was

Grouped based upon Yield Strength

Grouped materials (EN-GJS-500-14, EN-GJS-600-3); Grouped materials (EN-GJS-600-10, EN-GJS-700-2)

ISO #	ASTM #	Type of Stock	UTS MPa (ksi)	Tested UTS MPa (ksi)	Yield MPa (ksi)	Tested Yield MPa (ksi)	% EL	Tested % EL
EN-GJS-500-14	75-55-15	4" bar	500 (72.5)	81.8	400 (58)	410 (59.5)	14	18
EN-GJS-600-3	80-55-06	4" bar	600 (87.0)	94.5	370 (54)	394 (57.1)	3	6
EN-GJS-600-10	600-10 SSDI	4" bar	600 (87.0)	91.9	470 (68.2)	507 (73.5)	10	17
EN-GJS-700-2	100-70-03	4" bar	700 (101.5)	108.3	420 (60.9)	467 (67.8)	2	3

Figure 1. Materials tested grouped and based upon similar yield strengths.

logical. One lower yield strength material combination and one higher yield strength material combination was chosen for this study.

MACHINABILITY TESTING BY DRILLING

The evaluation of machinability of gray cast iron has been done using a drilling test by Rundman et al.[2] In this work, the machinability of gray cast iron was described in terms of weight loss of a specimen, based upon drilling using a constant load and constant drilling time. The reason for this study was to relate machinability to the microstructural features of gray cast iron. The drilling test was selected because drilling and boring are typical material removal operations performed on cast iron.

A 1/8" titanium nitride-coated drill bit was used to drill approximately 20 to 30 holes in each specimen. A constant force of 20 lb. was applied to the drill and the drilling operation was performed for 90 seconds (1 ½ minutes) on each hole. The specimen was weighed prior to hardness and drilling and then after drilling a specified number of holes. In this study, they were able to show that higher alloyed irons had a lesser amount of weight loss compared to unalloyed irons, thereby using weight loss as a measure of machinability.

Machinability Testing by Single Point Turning

Machinability testing was performed from a modified single-point turning test to measure the orthogonal cutting forces required to remove a predetermined amount of material from a set of steel bars with a variance microstructure by Falecki et al.[3] To analyze a large range of microstructures, a modified Jominy end quench was used to create a gradient of microstructure along the length of three alloy steel bars.

The testing setup used a Kistler force platform with a lathe tool holder fixed with a cemented carbide tool insert. A spindle speed, linear feed rate, and depth of cut was performed on several sample specimens. To measure the cutting forces, the force platform was fixed to the cross slide of a standard lathe. Initial findings, in the report, suggested that as the microstructure transforms from martensitic to ferrite/pearlite, the Rockwell hardness and the cutting force on the cutting tool decreases.

A comparative machinability test using single point turning was also performed to investigate the optimal cutting parameters, by varying cutting speed and depth of cut, on austempered ductile irons (ADI) was performed by Akdemir et al.[4] In this study, a series of tests were conducted on ADI samples that were austempered at 900C (1652F) and quenched at 380C (716F). Cutting speed and depth of cut were varied, while the feed rate was held constant. Orthogonal cutting forces were measured as well as surface roughness and tool wear. One of the important goals for this study was to determine an optimal cutting parameter to achieve the desired surface roughness, low tool wear, and minimal cutting force.

Tool Wear and Tool Wear Types

Cutting tools are subjected to several conditions that create wear in the tool. Cutting forces, elevated temperatures, and friction all contribute to tool degradation and expected tool life. This not only affects the machined surface of the part produced, but it also contributes to the major factor in the overall machining costs. Several factors can affect tool wear as well, such as the type of cutting tool, material being machined, cutting speed, cutting feed rate, the depth of cut, and whether coolant is used.[5]

Typical wear patterns in cutting tools have been reported in literature and observed in practice. On lathe tooling, flank wear, crater wear, nose wear, and chipping of the cutting edge are typical regions of wear. On drilling tools, flank wear and crater wear are also found, but so are margin wear and chisel edge wear. Since wear is generally a gradual deterioration process, chipping tends to be a catastrophic failure event. Flank wear is generally attributed to sliding of the tool along the machined surface causing an abrasive type wearing action. Crater wear is also susceptible to the same abrasive wear but is mainly due to extreme cutting temperature and a chemical similarity between the tool and workpiece. Nose wear is a result of the same abrasive wear that causes flank wear. Chipping on the other hand, is the sudden breaking or failure of the cutting edge. This can be caused by mechanical shock or thermal fatigue. Chipping by mechanical shock can occur where a small crack or defect already exists in the cutting tool. Thermal fatigue occurs when the cutting tool is subjected to thermal cycling during interrupted cutting operations.

Causes of Tool Wear

Tool wear is a result of the materials being machined, tool material, tool geometry, and the cutting conditions.[5] Primarily there is adhesive wear, abrasive wear, oxidation, and corrosion. Adhesive wear is caused by small particles of the tool welding to the chip due to friction and are removed from the surface of the tool. Abrasive wear is caused when hard particles within the workpiece abrade and remove material from the cutting tool. Abrasive wear is also caused by an increase in cutting temperature as cutting speed increases. Since the hardness of tool decreases with increased cutting temperature, thermal softening leads to an increase in abrasive wear. Oxidation occurs when the binder of the cutting tool reacts with oxygen. This often is a result of severe temperatures during machining. Corrosion, or corrosive wear is a result caused by a chemical reaction between the tool, the work piece, and the cutting fluid. This type of wear is normally observed in the machining of titanium alloys.

Tool wear is found on various regions of a cutting tool but is typically found on the flank and tool nose, as in the case of a lathe insert. Flank wear is commonly found in all machining tools and is primarily caused by abrasion of the cutting edge.[5] As the cutting tool is forced into the workpiece, there is frictional heating. Initially, the tool is very sharp, however, after a brief wear-in period, the sharp cutting edge rounds off and wear increases slowly. Once wear progresses, the once sharp tool becomes rounded off even more, producing more friction, higher cutting temperatures, and then accelerated wear.

Nose radius wear, found on the nose radius of the tool, is similar to flank wear and can be a result of abrasion or tool fracture. If workpiece is extremely hard, severe abrasive wear can result in accelerated loss of cutting tool material. Hard spots in the material, or vibration due to excessive cutting forces can cause impact conditions and result in chipping of the tool causing tool fracture.

EXPERIMENTAL METHOD

To evaluate the machinability of SSFDI grades to conventional grades, two grades of SSFDI and two grades of conventional ductile iron were chosen. This represented a lower yield strength material and a higher yield strength material. EN-GJS-500-14 (SSFDI) was compared to EN-GJS-600-3 and EN-GJS-600-10 (SSFDI) was compared to EN-GJS-700-2. EN-GJS-450-10 was also tested but only tested as standalone material.

The machining tests performed on the different materials were drilling, milling, and single point turning. All test materials provided were 4-inch diameter bar stock.

TESTING PARAMETERS

A testing matrix was formed to specify the cutting speeds in surface feet per minute (SFM), feed rate in inches per revolution (in/rev), and depth of cut in inches (in) for each machining process, see Table 1. Surface cutting speeds were chosen from low, medium, and high recommended speeds commonly used for machining conventional ductile iron grades using carbide cutting tools. In addition, surface speeds were also chosen resulting in an overlap of speed ranges between the lower and higher strength materials. Feed rates chosen were commonly used low and high rates. A consistent depth of cut was chosen based upon the equipment used for the test.

Drilling

Drilling tests were performed using a 3/8" – 2 flute ported carbide drill (Garr tool series 1280KH #25771), to a drill depth of 1.125." This size drill was required to achieve the recommended surface speed on a standard milling machine. Through-port cooling was used with a 5% coolant concentration and a pump pressure of 500 psi. Through-port cooling was used to prevent chip packing and promote chip evacuation from the drilled holes. With the sample material being 4-inch diameter bar stock, individual 2-inch-long pucks of material were cut, faced off, and then clamped in a vise mounted on the Kistler dyno. A series of 42 holes were drilled in each sample. Drilling was not done on the outer perimeter of the test samples to avoid the outer skin.

Force measurements were obtained using a Kistler 9265B piezoelectric dynamometer. This unit provided orthogonal cutting forces for the drilling operation as well as the milling operation. A new drill was used for each force measurement. Force time histories for 3 consecutive holes were used to average the drilling forces at the beginning of the testing cycle.

Table 1. Testing Matrix of Grouped Materials for Rough Turning, Milling, and Drilling

Material	Machining Operation	Recommended Machining Speed (SFM)	Feed Rate (in/rev)	Depth of Cut (in)
EN-GJS-500-14 (75-55-15)	Rough Turning	700, 900, 1100	0.013 and 0.022	0.150"
	Milling	850, 1050	0.004 and 0.012	0.125"
	Drilling	400, 550, 700	0.003 and 0.012	1.125"
EN-GJS-600-3 (80-55-06)	Rough Turning	700, 900, 1100	0.013 and 0.022	0.150"
	Milling	450, 650, 850	0.004 and 0.012	0.125"
	Drilling	400, 550, 700	0.003 and 0.012	1.125"
EN-GJS-600-10 (600-10 SSDI)	Rough Turning	500, 700, 900	0.013 and 0.022	0.150"
	Milling	650, 850	0.004 and 0.012	0.125"
	Drilling	250, 400, 550	0.003 and 0.012	1.125"
EN-GJS-700-2 (100-70-03)	Rough Turning	500, 700, 900	0.013 and 0.022	0.150"
	Milling	450, 650	0.004 and 0.012	0.125"
	Drilling	250, 400, 550	0.003 and 0.012	1.125"

Milling

Since the test material was round bar, milling tests were carried out by cutting a circular pattern. Climb milling was performed as this resulted in a reduced chance of re-cutting discharged chips as well as reduced tool rubbing at the beginning of the cut. A ½" – 5 flute square end mill (5 FL Garr #50056) was used at a standard depth of cut of 0.125." A step-over of 75% of the cutter diameter was used in each test. Test samples were milled dry as no coolant was used during these tests.

Milling forces for all material grades were measured with a new end mill on the first test sample. Since the cutting pattern is circular, X and Y orthogonal forces were averaged into one radial force value.

An average of three consecutive circular cuts were used to calculate the radial force.

Rough OD Turning

Rough OD turning tests were carried out on 13-inch test samples by cutting a standard depth of cut. The cut length was approximately 12 inches with a consistent 0.150” depth of cut for each pass. Each sample was prepped by first cutting the outer skin prior to performing the cutting tests with a separate insert. No coolant was used with the turning tests. A 2-axis turret lathe was used for all turning. Sandvik CNMG 432-MR 4425 inserts were used for the experiment. No tool force measurements were obtained from this test due to the incompatibility of this turret lathe and force dyno.

RESULTS and DISCUSSION

DRILLING WEAR

When drilling 600-3, early tool failure was observed at the high surface speed and high feed rate of 700 SFM and 0.012 in/rev respectively, see Figure 2. Early tool failure was also observed when drilling 500-14, but this happened a little after 5 minutes in cut which equated to 422 holes. 450-10 performed well and drilled a total of 1302 holes with a cutting time of 17 minutes. When the feed rate dropped to 0.003 in/rev, 500-14 performed very well and seemed to settle in after an initial increase in tool wear. 756 holes were drilled at this speed and feed rate, with an approximate cut time of 42 minutes as seen in Figure 3.

High Surface Speed – High Feed Rate

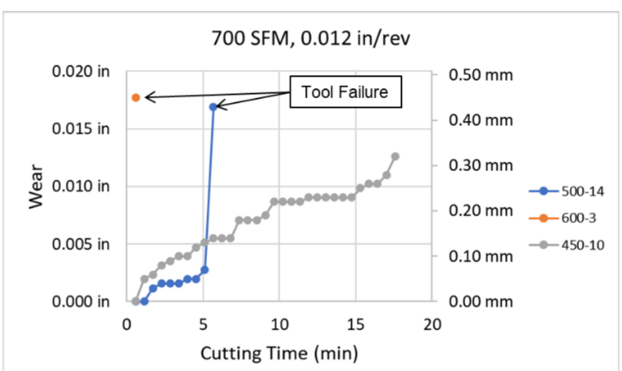

Figure 2. Drill wear results for 700 SFM at a feed rate of 0.012 in/rev.

High Surface Speed – Low Feed Rate

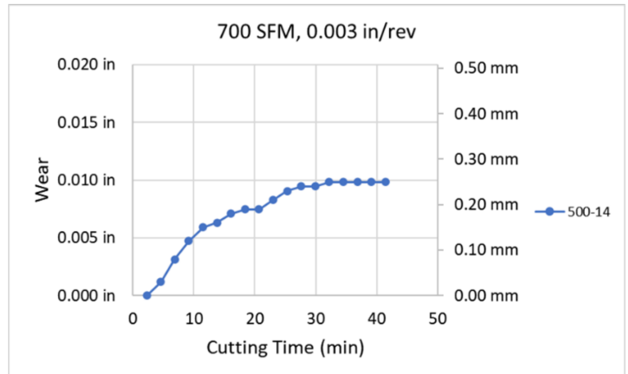

Figure 3. Drill wear results for 700 SFM at a feed rate of 0.003 in/rev.

Mid Surface Speed – High Feed Rate

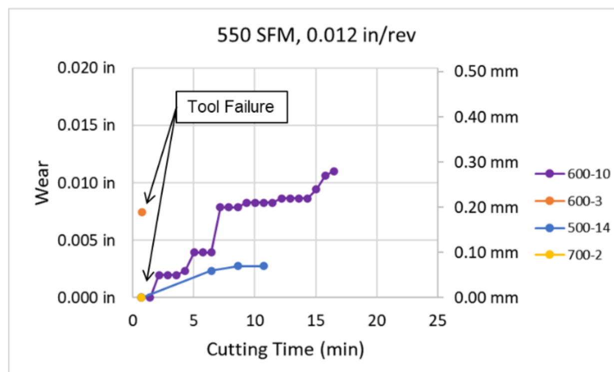

Figure 4. Drill wear results for 550 SFM at a feed rate of 0.012 in/rev.

When drilling 700-2 and 600-3, tool failure was observed quickly at 550 SFM and 0.012 in/rev. 500-14 performed well at 550 SFM, with no significant wear after 12 minutes in cut, or 630 holes, and seem to settle in as seen in Figure 4. 600-10 also performed well at 550 SFM and 0.012 in/rev to achieve a reasonable wear curve that lasted approximately 17 minutes, or 966 holes, before wear was excessive (Figure 5).

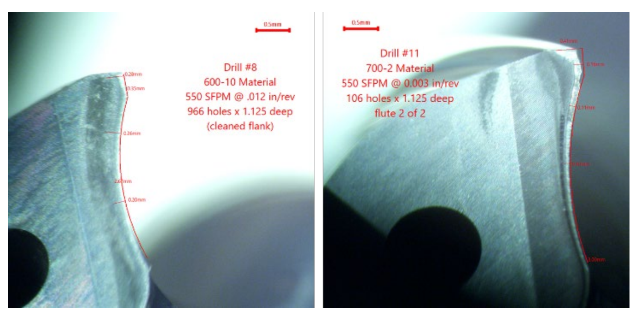

Figure 5. Drill wear images taken after the final cut for 600-10 at 550 SFM and 0.012 in/rev (left - 966 holes) and 700-2 at 550 SFM and 0.003 in/rev (right – 106 holes).

Low Surface Speed – High Feed Rate

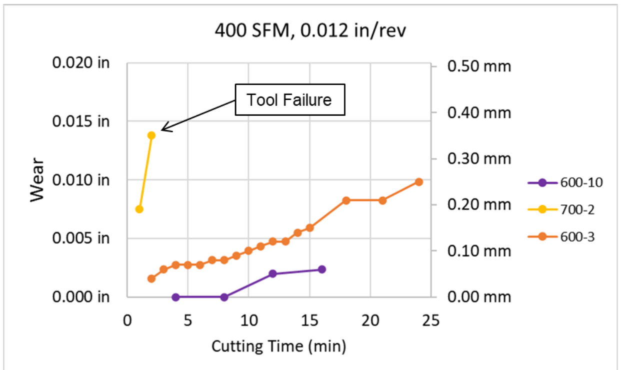

Figure 6. Drill wear results for 400 SFM at a feed rate of 0.012 in/rev.

600-3 was only able to run at 400 SFM (low surface speed) for achievable wear curve after 1008 holes and showed that the tool held on well, while subtly increasing in wear after 15 minutes of cut time, see Figure 6. The 700-2 did not perform well at 400 SFM (mid surface speed) showing higher tool wear early on, even though 400 SFM seemed to be a sweet spot for force as shown in Figure 6. However, 700-2 was only able to be cut at the lowest surface speed of 250 SFM and lowest feed rate of 0.003 in/rev to achieve a reasonable wear result.

Drilling Forces

In Figures 7 and 8, most of the cutting forces remained relatively consistent across all surface cutting speeds and feed rates. However, Figure 7, 700-2 showed a high force at 250 SFM, a significant decrease in force at 400 SFM, and then a high force at 550 SFM. It appeared as if 700-2 material was able to cut better at 400 SFM, but the resulting wear indicated this was not the case. An additional set of experiments was conducted to verify this observed anomaly.

High Feed Rate

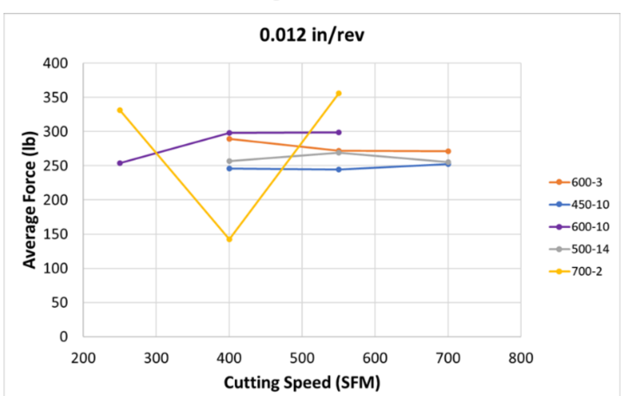

Figure 7. Average drilling forces of all materials drilled at 0.012 in/rev.

Low Feed Rate

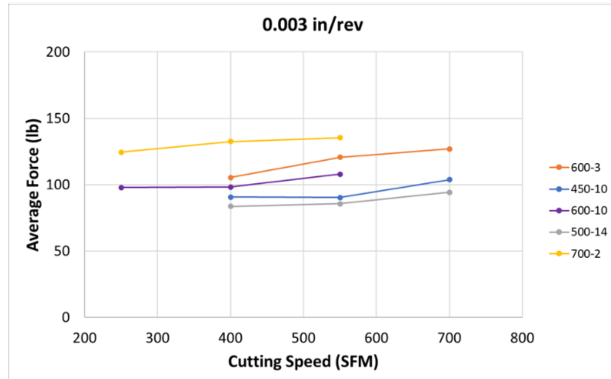

Figure 8. Average drilling forces of all materials drilled at 0.003 in/rev.

Drilling Summary

Table 2 shows the comparison of the performance of the SSFDI and conventional grades at their specific speeds. This table lists some of the highlights observed and color codes them into four categories: tool failure, very high tool wear, moderate to high wear, and normal wear. With tool failure, the test was stopped immediately. If the spindle loads were high or there was high amount of drill noise, this indicated very high tool wear, and the test was also stopped. For moderate to high drill wear, the tests were concluded once the drill was beyond its usable life. For normal wear, the drills were still considered useable. Although these observations are subjective, it summarizes them in a reasonable format.

500-14 and 600-3 Grade Comparison

In general, 500-14 SSFDI (lower yield strength grade) was able to be drilled better at all speeds and feed rates compared to conventional grade 600-3 with a significant amount of increased cut time. Although 0.0012 in/rev was an extreme feed rate at 700 SFM, it was adequate at 0.003 in/rev. Also seen in Table 2, drilling forces for 500-14 were lower compared to 600-3. At low feed rates of 0.003 in/rev, the forces were at least 20% lower. At a higher feed rate of 0.012 in/rev, the 500-14 drilling forces were comparable, but still lower than 600-3. Conventional grade 600-3 was only able to be successfully drilled at the lowest surface cutting speed specified. Even though force measurements were obtained at higher surface speeds, the drills wore quickly and failed during the first series of 42 holes.

600-10 and 700-2 Grades Comparison

For the higher yield strength grades, 600-10 outperformed 700-2 at all cutting speeds and feed rates. 600-10 performed well at 550 SFM and excellent at 400 SFM. Because 600-10 showed excellent performance at the mid-cutting speed range of 400 SFM, testing at 250 SFM was not done, as this would have resulted in a similar outcome. In comparison, 700-2 did not perform well at either the high or mid surface cutting speed. 700-2 had tool failures at nearly all cutting speeds except at 250 SFM and 0.003 in/rev where a measurable performance was achieved.

Drill forces for 600-10 were significantly lower in all cases compared to 700-2. On average, drilling forces were approximately 25% lower with 600-10. Even though 600-10 was not tested for wear at 250 SFM, it was tested for drilling force. This was the same case for 700-2 force measurements at 400 SFM at 0.003 in/rev, as it was tested for force, but not for wear.

Table 2. Drilling Test Summary Table

		Cutting Speed				
Material		**250 SFM**	**400 SFM**	**550 SFM**	**700 SFM**	
EN-GJS-500-14 (75-55-15)	Force		Tool Force approx. 20% lower than 600-3	Tool Force approx. 29% lower than 600-3	Tool Force approx. 25% lower than 600-3	**Feed Rate = 0.003 in/rev**
	Wear		Did not test	Excellent - No significant wear after 16 min (358 holes)	Excessive Wear after 41 min (756 holes)	
EN-GJS-600-3 (80-55-06)	Force			Tool Failure (42 holes)	Tool Failure (42 holes)	
	Wear		Did not test			
EN-GJS-600-10 (600-10 SSDI)	Force	Tool Force approx. 21% lower than 700-2	Tool Force approx. 26% lower than 700-2	Tool Force approx. 20% lower than 700-2		
	Wear	Did not test	Excellent - No significant wear after 19 min (210 holes)	Excessive Wear after 16 min (358 holes)		
EN-GJS-700-2 (100-70-03)	Force			Tool Failure after 7 min (106 holes)		
	Wear	Excessive Wear after 45 min (294 holes)	Did not test			
		Cutting Speed				
Material		**250 SFM**	**400 SFM**	**550 SFM**	**700 SFM**	
EN-GJS-500-14 (75-55-15)	Force		Tool Force approx. 10% lower than 600-3	Tool Force approx. 1% lower than 600-3	Tool Force approx. 6% lower than 600-3	**Feed Rate = 0.012 in/rev**
	Wear		Did not test	Excellent - No significant wear after 11 min (630 holes)	Tool Failure after 6 min (422 holes)	
EN-GJS-600-3 (80-55-06)	Force			Tool Failure (42 holes)	Tool Failure (42 holes)	
	Wear		Excessive Wear after 24 min (1008 holes)			
EN-GJS-600-10 (600-10 SSDI)	Force	Tool Force approx. 23% lower than 700-2	Tool Force approx. 50% higher than 700-2	Tool Force approx. 16% lower than 700-2		
	Wear	Did not test	Excellent - No significant wear after 16 min (672 holes)	Tool Failure after 17 min (966 holes)		
EN-GJS-700-2 (100-70-03)	Force	Tool Failure after 13 min (336 holes)	Tool Failure (84 holes)	Tool Failure (42 holes)		
	Wear					

Color Code	Normal Wear	Moderate to High Wear
	Very High Tool Wear	Tool Failure

<u>Milling Wear</u>

Milling tests were first performed at the highest surface speed and highest feed rate for all material grades. Upon completion, it was observed the SSFDI material performed very well, and the tool wear was minimal, see Figures 9 and 10. Observable wear results for the conventional materials were achieved, however, rather than running the SSFDI grades at lower surface speeds and feed rates, it was decided to increase the surface speed above the recommended speed. Surface speeds were increased to 200 SFM above each maximum value. This resulted in an approximate 24% increase in surface cutting speed for 500-14 and an approximate 31% increase for 600-10.

The increased surface cutting speed then resulted in an observable wear curve for the 500-14 after approximately 37 minutes of cut time as seen in Figure 11.

The 600-10 was tested to approximately 27 minutes of cut time, at which the wear results followed the observed wear when cutting 500-14 at the same speed with no significant wear. To determine when the cutting edge would eventually fail, more samples should be tested.

Because the cutting speed of 600-10 was increased 200 SFM above the recommended cutting speed, the results are shown in Figure 12 along with the high surface speed results of 500-14, 600-3, and 450-10 for comparison. Even though 600-10 was grouped as a higher yield strength material, the milling performance was excellent and similar to the performance of a lower strength material.

450-10, 500-14, and 600-3 wear comparison

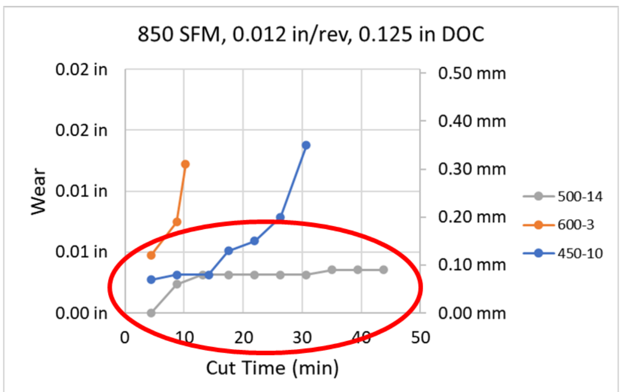

Figure 9. Lower strength material comparison of tool wear for the original high cutting speed of 850 SFM and high feed rate 0.012 in/rev.

600-10 and 700-2 wear comparison

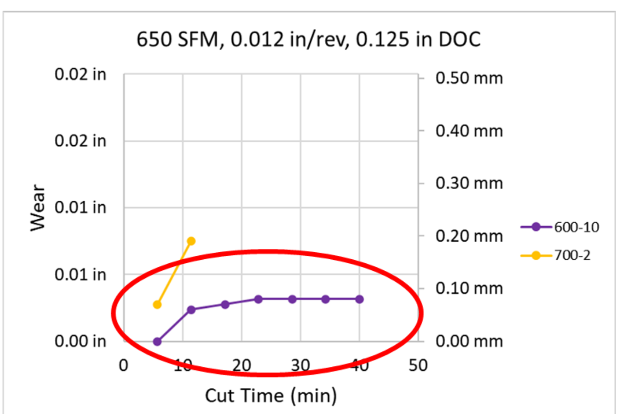

Figure 10. Higher strength material comparison of tool wear for the original high cutting speed of 650 SFM and high feed rate 0.012 in/rev.

500-14 wear comparison

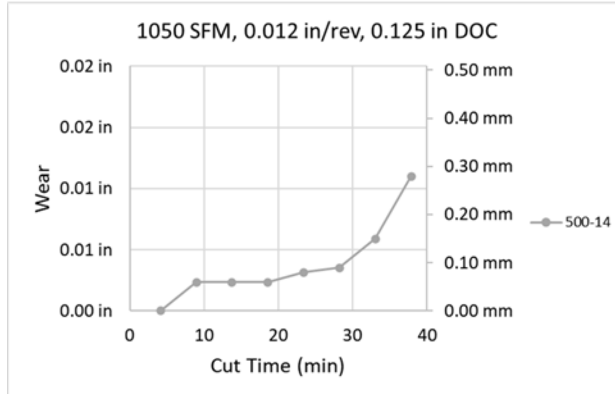

Figure 11. 500-14 tool wear from increasing high cutting speed from 850 SFM to 1050 SFM.

450-10, 500-14, 600-3, and 600-10 wear comparison

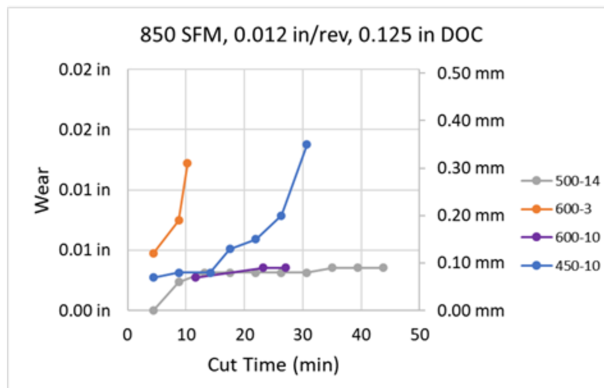

Figure 12. 600-10 tool wear from increasing high cutting speed from 650 SFM to 850 SFM.

Milling Forces

Milling forces obtained for all material grades were measured with a new end mill during the initial cut. Since the cutting pattern is circular, X and Y orthogonal forces were averaged into one radial force value. Three circular cuts were recorded to calculate each average. Average radial forces are shown in Figure 13. The results show that both SSFDI materials behaved similarly as surface speed was increased. Conventional material, 700-2 and 600-3, both had early tool failure at the original corresponding high surface speeds.

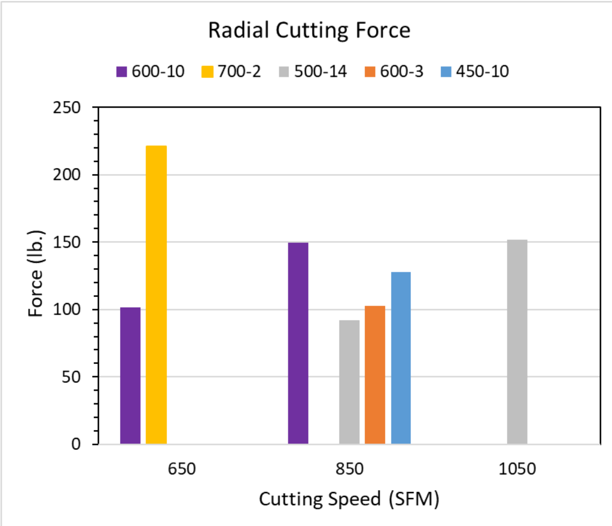

Figure 13. Radial cutting force measurements for all material grades milled.

Rough OD Turning Wear

For the wear results from the turning tests, it was observed that there were two types of tool wear present, nose wear and flank wear. In most cases, there was a consistent failure of the insert nose well before the flank wear was significant as seen in Figures 14 to 17. For example, at the high surface speed and high feed rate, conventional grade 600-3, the nose of the cutting insert failed before 3 minutes in cut as indicated in Figure 14. At the lower feed rate of 0.013 in/rev, the cutting insert was able to last twice as long, however, this was only approximately 8 minutes in cut for 500-14.

High Surface Speed – High Feed Rate

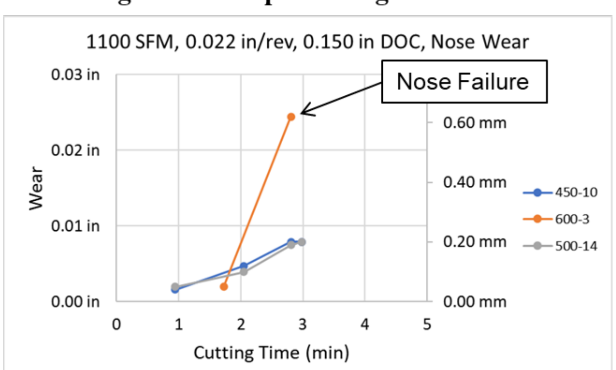

Figure 14. Cutting insert nose wear for 1100 SFM and 0.022 in/rev.

High Surface Speed – High Feed Rate

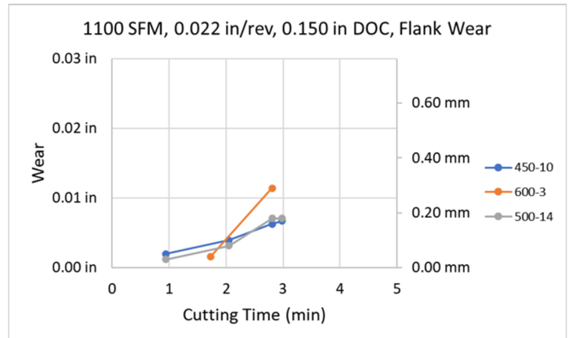

Figure 15. Cutting insert flank wear for 1100 SFM and 0.022 in/rev.

High Surface Speed – Low Feed Rate

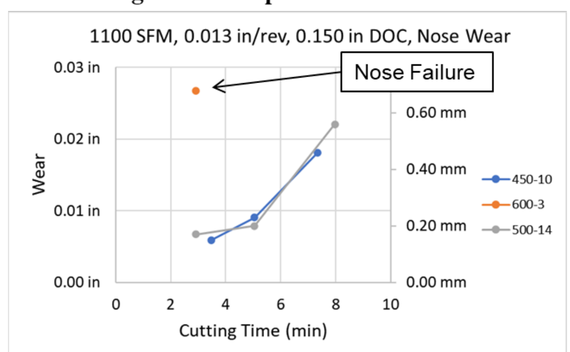

Figure 16. Cutting insert nose wear for 1100 SFM and 0.013 in/rev.

High Surface Speed – Low Feed Rate

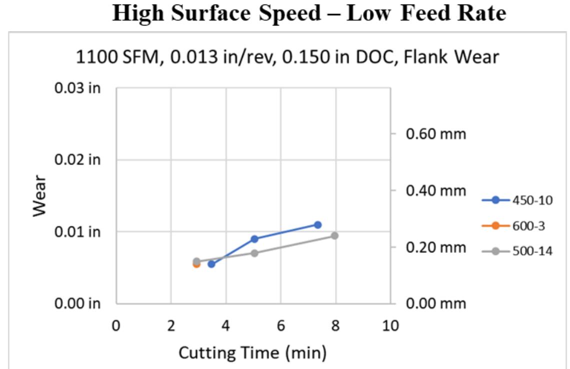

Figure 17. Cutting insert flank wear for 1100 SFM and 0.013 in/rev.

At 900 SFM there is an overlap between the lower strength and higher strength grouped materials. Since 900 SFM is the mid-range speed for the lower strength grades and the high range for the higher strength grades all the ductile iron grades were included. Cutting 700-2 at this surface speed and feed rate resulted in early tool failure. 600-10 SSFDI was able to last approximately 5 minutes in cut before its tool failed. 500-14 and 600-3 started to show more even flank wear, as shown in Figure 19, but was not able to handle the high feed rate.

Mid/High Surface Speed – High Feed Rate

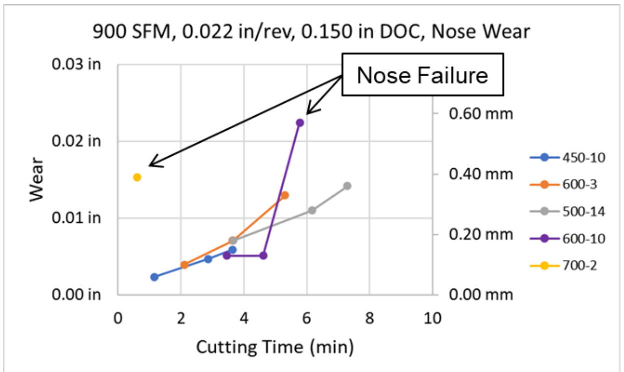

Figure 18. Cutting insert nose wear for 900 SFM and 0.022 in/rev.

Mid/High Surface Speed – High Feed Rate

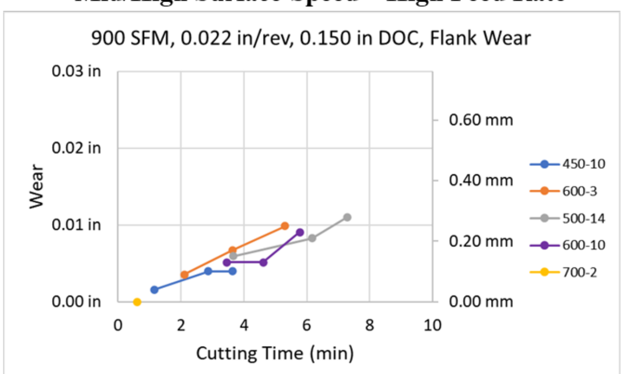

Figure 19. Cutting insert flank wear for 900 SFM and 0.022 in/rev.

Figure 20 shows the resulting insert wear for 500-14 and 600-3 after the final cut. As was typically observed, SSFDI grades lasted longer than conventional grades. For this figure, 500-14 lasted approximately 7.3 minutes and 600-3 lasted 5.3 minutes.

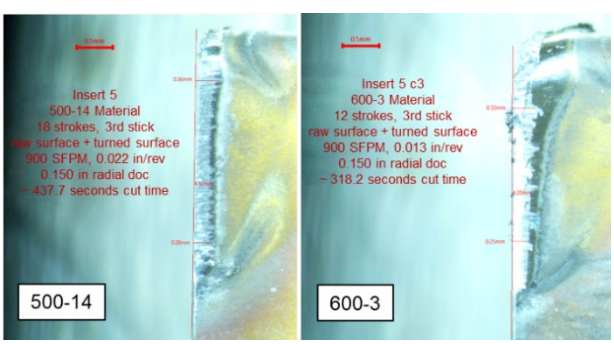

Figure 20. Insert wear images for 500-14 and 600-3 cutting at 900 SFM and 0.022 in/rev. Scale bar in the image is 0.5 mm.

When surface cutting speed dropped to low speed of 700 SFM for 500-14 and 600-3, tool life begins to increase for both high and low feed rates, see Figures 21 to 23. Insert wear is primarily on the flank and no nose failure was observed. 700 SFM is the lowest surface speed used to test 500-14 and 600-3.

For 600-10 and 700-2 grades at 700 SFM, early insert failure was observed at the insert nose for both 0.022 in/rev and 0.013 in/rev. The 700-2 finally lasted longer than just a single pass, but no more than two.

Low/Mid Surface Speed – Low Feed Rate

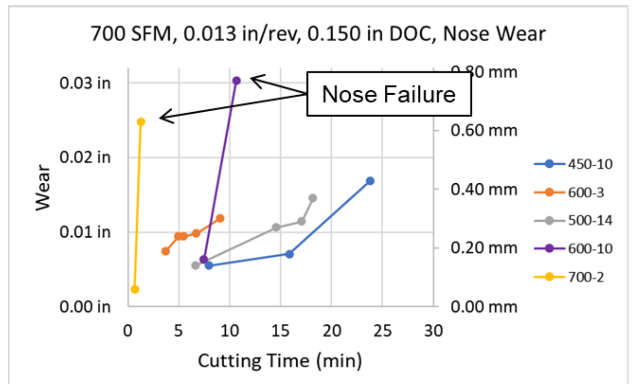

Figure 21. Cutting insert nose wear for 700 SFM and 0.013 in/rev.

Low/Mid Surface Speed – Low Feed Rate

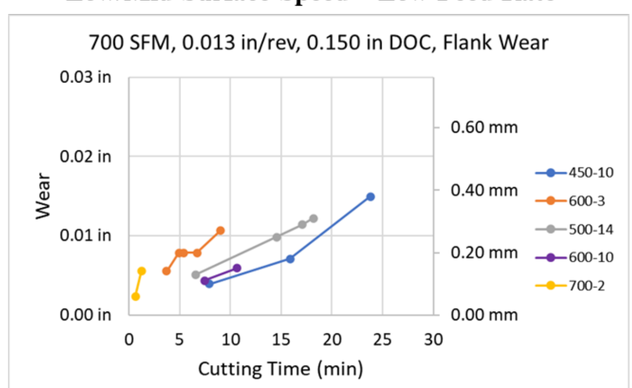

Figure 22. Cutting insert flank wear for 700 SFM and 0.013 in/rev

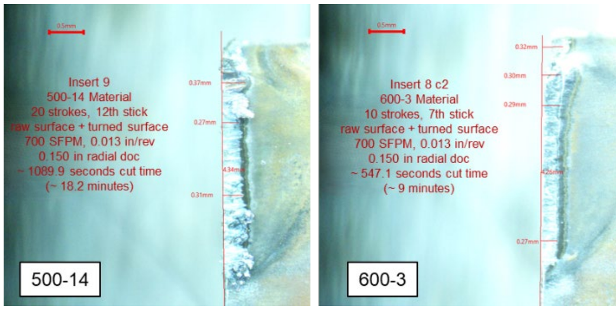

Figure 23. Insert wear images for 500-14 and 600-3 cutting at 700 SFM and 0.013 in/rev. Scale bar in the image is 0.5 mm.

At 500 SFM and 0.022 in/rev, 700-2 retained similar flank and nose wear and lasted four lengths of cut on one sample, see Figures 24 and 25. The 600-10 remained nearly constant in wear until the eighth test sample, where the nose finally failed, however it did stay low in flank wear even with the nose failing, as seen in Figure 26.

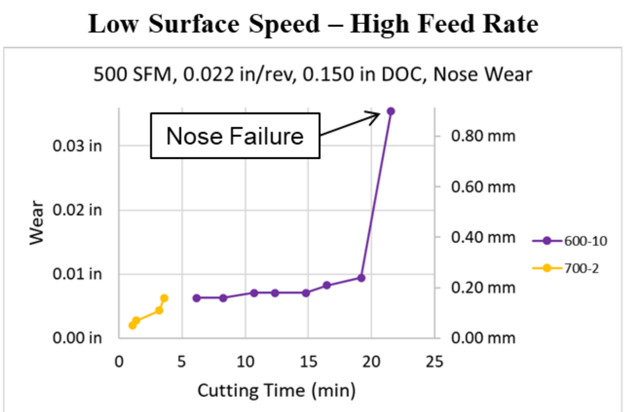

Figure 24. Cutting insert nose wear for 500 SFM and 0.022 in/rev.

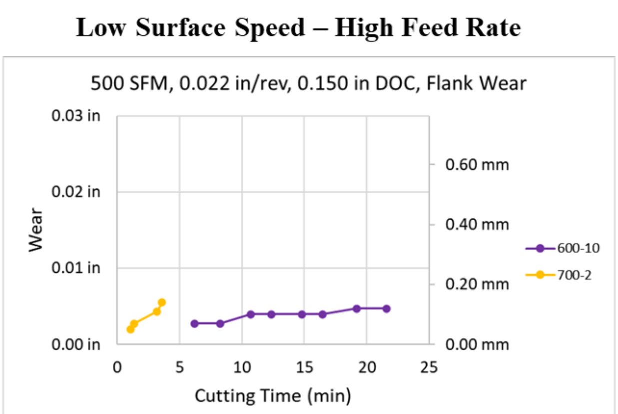

Figure 25. Cutting insert flank wear for 500 SFM and 0.022 in/rev.

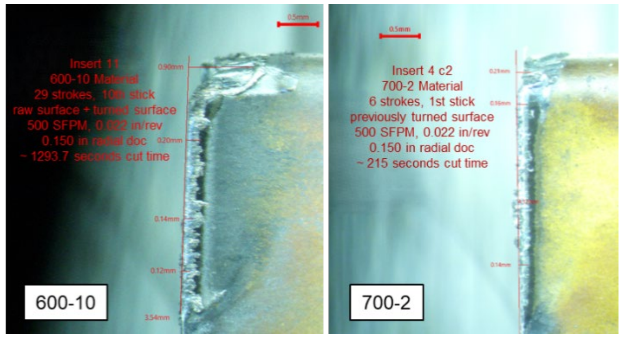

Figure 26. Insert wear images for 600-10 and 700-2 cutting at 500 SFM and 0.022 in/rev. Scale bar in the image is 0.5 mm.

Turning Summary

A summary of the rough OD turning test is listed in Table 3. Since there are many test results, this table lists some of the highlights observed and color codes them into four categories: tool failure, very high tool wear, moderate to high wear, and normal wear. With tool failure, the test was stopped immediately. If the lathe spindle loads were high or there was a high amount of tool noise, this indicated very high tool wear, and the test was also stopped. For moderate to high tool wear, the tests were concluded once the insert was beyond its useable life. For normal wear, the inserts were still considered useable. Although these observations are somewhat subjective, it summarizes them in a reasonable format.

500-14 and 600-3 Grade Comparison

Overall, the testing surface speed of 1100 SFM proved to be an extreme speed for all low yield strength grades. SSFDI performed better than conventional grade, however, the cut time was no greater than 3 minutes at a high feed rate and 8 minutes at a low feed rate. As the surface speed was reduced to 900 SFM, the cut time was increased, but not by a significant amount of time. Once the surface speed was reduced to 700 SFM, the lathe inserts were able to last longer. In all cases, the insert used to cut 500-14 lasted approximately 2x longer than inserts used to cut 600-3.

600-10 and 700-2 Grade Comparison

For the higher yield strength grades, the high surface speed of 900 SFM also proved to be an extreme speed. Again, the SSFDI outperformed the conventional grade, but the cut time was less than 7 minutes for both feed rates. At surface speeds of 700 SFM and 500 SFM, 600-10 outperformed 700-2 significantly by lasting approximately 5x longer before the insert was beyond its useful life.

Table 3. Turning Test Summary Table

		Feed Rate = 0.013 in/rev				Feed Rate = 0.022 in/rev			
		Cutting Speed (SFM)				Cutting Speed (SFM)			
Material		**500**	**700**	**900**	**1100**	**500**	**700**	**900**	**1100**
EN-GJS-500-14 (75-55-15)	Wear		Moderate Flank Wear after 18.2 min	Excessive Flank Wear after 9.8 min	Excessive Nose and Flank Wear after 8 min		Moderate Flank Wear after 14 min	Excessive Flank Wear after 7.3 min	Excessive Flank Wear after 3 min
EN-GJS-600-3 (80-55-06)	Wear		Moderate Flank Wear after 9 min	Nose Failure after 4.6 min	Nose Failure after 2.9 min in cut		Mod. Flank Wear and Nose Failure after 5.3 min	Nose Failure after 5.3 min	Nose Failure after 2.8 min
EN-GJS-600-10 (600-10 SSDI)	Wear	Moderate Flank Wear after 25 min	Moderate Flank Wear and Nose Failure after 10.6 min	Nose Failure after 7.1 min		Moderate Flank Wear and Nose Failure after 21.6 min	Moderate Flank Wear and Nose Failure after 8.1 min	Moderate Flank Wear after 5.8 min	
EN-GJS-700-2 (100-70-03)	Wear	Mod. Flank Wear and Extreme Nose Wear after 5 min	Nose Failure after 75.4 sec	Nose Failure after 30.4 sec		Nose Failure after 3.6 min	Nose Failure after 38.7 sec	Nose Failure after 36.2 sec	

Color Code	Normal Wear	Moderate to High Wear
	Very High Tool Wear	Tool Failure

Brinell Hardness

Hardness measurements were taken for each of the test materials and are presented in Table 4. A minimum of four measurements were performed for the center section, mid-radius, and outer edge on each sample. Figure 27 shows the locations of the measurements. Measurements were then averaged for the final hardness value.

Table 4. Brinell Hardness Measurements on Ductile Iron Grades used in the Machinability Tests

	500-14	**600-3**	**450-10**	**600-10**	**700-2**
Center HBW	192±2	218±3	180±2	213±2	264±6
Mid-Radius HBW	190±5	217±9	182±8	214±1	269±5
Edge HBW	183±2	201±3	175±7	213±0	268±3

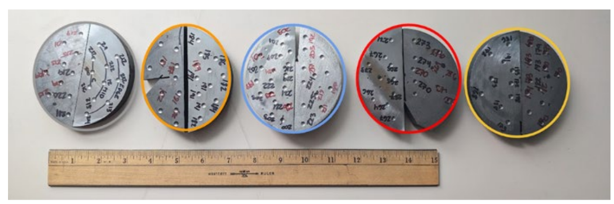

Figure 27. Brinell hardness measurements along the center, mid-radius, and edge of the test samples.

Metallography

Table 5 lists the graphite, ferrite, and pearlite percentages for the samples tested. Photomicrographs were taken 100X in the etched condition to reveal the pearlitic appearance.

Table 5. Graphite, Ferrite, and Pearlite Percentages for all Ductile Iron Grades used in Machinability Tests

Sample	Graphite (%)	Ferrite (%)	Pearlite (%)
500-14 Edge	11	85	5
500-14 Mid-radius	15	78	8
500-14 Center	12	76	12
600-3 Edge	10	59	31
600-3 Mid-Radius	13	23	64
600-3 Center	14	38	48
450-10 Edge	11	81	8
450-10 Mid-radius	13	44	44
450-10 Center	12	62	26
600-10 Edge	15	84	1
600-10 Mid-radius	16	83	1
600-10 Center	14	83	3
700-2 Edge	12	4	84
700-2 Mid-radius	13	6	81
700-2 Center	9	5	87

For the SSFDI grades of 500-14, 600-10, and 450-10, the samples are mostly ferritic and lower in pearlite percentages than 600-3 and 700-2 grades which plays an important role in the ease of machining.

Conventional grades 600-3 and 700-2 have an overall higher percentage of pearlite as compared to the SSFDI grades which play a role in being harder to machine. The 700-2 is mostly pearlitic with a low percentage of ferrite and was the hardest of all the ductile iron grades to machine. Graphite percentages are similar between all sample materials.

CONCLUSIONS

In this experiment, the machinability of two SSFDI grades were compared with two conventional grades by drilling, milling, and single point turning. The 500-14 was compared against 600-3 and 600-10 was compared against 700-2. These specific grades of ductile iron were evaluated based upon their yield strength similarities. Overall, the machinability of SSFDI is far better than conventional grades.

With drilling, the 500-14 was able to be drilled at surface speeds where 600-3 was not. This was also the case for 600-10 vs. 700-3. This indicates that spindle speeds when drilling SSFDI can be higher, thereby decreasing overall machining time, or by maintaining slower surface speeds resulting in longer tool life and reducing tooling costs. Another benefit was the lower cutting forces observed leading to reduced loading on machine components.

With milling, SSFDI grades were able to be machined at surface speeds higher than suggested for conventional grades. This was an unexpected finding. 500-14 was able to be increased by approximately 24% over the highest recommended cutting speed, and 600-10 was able to be increased by approximately 31%. Since feed rate is tied to spindle speed by how much the tool advances into the workpiece per revolution, increasing cutting speeds helps to significantly decrease overall machining time. If a slower surface cutting speed is desired, milling SSFDI grades will significantly improve cutter life and reduce tooling change outs, thereby reducing tooling costs.

Rough OD turning of SSFDI, and conventional grades also resulted in some unexpected findings. First, the recommended surface cutting speeds on the high end were too aggressive for all the cutting tests. It was not until testing was performed at the low end of the surface speed range was carried out that tooling inserts were able to survive. However, it was observed that 500-14 had 2 times the tool life compared to 600-3 and 600-10 had 5 times the tool life compared to 700-3. This is also significant for overall machine-related costs. As was the case with drilling and milling, cutting at a faster speed, or cutting at a slower speed to extend tool life greatly decreases machining costs.

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