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Effect of Casting Method and Surface on Ductile Iron Machinability

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ABSTRACT

Machinability measurements were conducted during face cutting of ferritic/pearlitic ductile irons, produced by the continuous casting process (8" diameter cylindrical bars), and by sand castings (10" diameter, 5J-AFS discs). These two processes provided significantly different cast surface topology, near-surface microstructure ("casting skin") and graphite nodule count in the casting body. Cutting forces and tool wear were measured for different machining parameters. The continuous cast ductile iron provided better surface machinability because, in this case, the casting skin had less adverse effect on tool wear and cutting energy than in the case of the sand castings. However, sand castings showed better machinability of the casting body because they had a finer graphite structure. Quantitative microstructure analysis was used to correlate graphite structure in ductile iron to chip formation. These tests provide data that can be used for machining process planning.

Keywords: ductile iron, machinability, sand casting, continuous casting, tool force, tool wear, graphite nodule, cast iron

INTRODUCTION

The cast iron material family, which consists of gray iron with flake graphite, compacted graphite iron (CGI) with compacted graphite, and ductile iron with nodular graphite, is considered to have good machinability relative to steel. Additional improvements in the machinability of ductile iron castings will reduce consumption of both energy and tool materials, thereby providing benefit to foundry profitability and the environment. The following casting features are discussed with their relevance to ductile iron machinability: a) casting dimensional tolerance b) "casting skin," c) metal matrix and graphite structure, and d) age strengthening. These casting features depend on many technological parameters such as molding practice, Mg-treatment and inoculation, cooling rate, and cast iron chemical composition. Additionally, non-metallic inclusions and mechanical properties of micro-constituents may also affect machinability.

The so called "casting skin" is formed by iron in contact with the mold at the time of solidification. Various defects such as porosity, non-metallic inclusions from molding sand and/or high-temperature reaction products, and graphite structure irregularities are present in the casting skin. Image analysis techniques have been applied by different authors to define the depth of the casting skin in various cast irons.[1,2,3,] The skin region is present on essentially all iron castings and can significantly influence casting performance. Goodrich and Lobenhofer[4] showed that ductile iron castings with the skin present have lower tensile strength and elongation than castings with the skin machined off. In the majority of tests made by these authors, the tensile bars with skin did not meet ASTM A536 minimums; however, bars with the skin machined off did meet the standard. In gray iron the skin region is known to have deleterious effects on machinability. This effect is observable in tool force measurements where specific cutting energy in the skin region can be double that of the body region.[1] The skin of ductile iron castings is considered by foundry engineers to be deleterious to machinability as well. Boonmee and Stefanescu[2] proposed a skin formation mechanism in CGI driven by magnesium diffusion that allows for depletion of the magnesium in the skin region by reactions. A similar mechanism was proposed later by Boonmee, et al.[3] for ductile iron where micro-segregation of magnesium during solidification produced flake graphite structures.

Geometrical inconsistencies, in particular flatness, are an important characteristic of the casting skin that can have significant influences on tool life. In a paper by Voigt et al.,[5] a compelling discussion is provided for how serious flatness variations can be for tool life when machining ductile iron castings. For instance, with a 0.06-inch depth of cut, a change in flatness resulting in an average 0.01 inch depth of cut increase can decrease tool life by 20%. Dimensional tolerance is dependent on the casting processing. For example, continuous cast irons in permanent mold can be expected to have lower flatness variations than in one-time-use sand molds because of the difference in the rigidity of molds and the tolerances of the molds themselves.

A general perception among metallurgists is that cast iron with more ferrite (or a "softer iron") will machine better than one with more pearlite instead of ferrite. There is certainly published research to support this perception. One such paper was presented by Phillips[6] where ductile iron cylinders, cast in green sand, with diameters of 8.25" were used in a tool wear machinability experiment. Using tungsten-carbide tools, he found that ferritic ductile iron provided better tool life than pearlitic ductile iron. For a comparison, some extrapolation of the tool wear data is required but the improvement was about tenfold. Another paper reaching a similar, but more detailed, conclusion used continuously cast ductile iron.[7] In this work, higher pearlite content appeared to increase the tool wear rate. According to statistical analysis, the thickness of the pearlite colonies was the greatest controller of tool wear rate. As the average colony thickness increased, so did the wear rates. With similar pearlite contents, an iron with higher copper was concluded to make tool wear rates higher because of the strengthening effect of copper in solid solution. It is noteworthy that as pearlite contents increased, the nodule counts decreased, so there could have been overlap in the observations of their effect on machinability. Some irons with more pearlite may be rated to have better machinability. In a paper by Gagné and Labrecque, drilling experiments to a depth of 80cm were reported as showing a lower thrust force of ~100 *N* (~20%) and 0.6 Nm (~40%) less torque when machining a 18% pearlite iron over a ~0% pearlite iron.[8] The increased machinability was attributed to a chip-breaking effect of the pearlite. Thus, it is possible that a mixed ferrite/pearlite microstructure may provide the best machinability characteristics under some circumstances.

Variables that affect hardness will also affect machinability but the effect on machinability will not be directly proportional to the effect on hardness. For instance, the appearance of small carbides in a ferrite/pearlite casting may slightly increase the hardness while severely decreasing machinability whereas a similar increase in hardness caused by increasing pearlite content will have less effect on machinability.

The variety of ductile iron casting features that affect machinability will typically be present simultaneously. The combined influences can cause difficultly in separating the specific effects of these features on overall casting machinability. In particular, the "skin effect" relates together with casting surface tolerance, contamination of near cast surface region by products of metal/mold reactions, and the influence of a high cooling rate on graphite nodule size and the metal matrix. Whereas ductile iron castings from sand molds typically have the aforementioned casting body and near-cast surface features while continuously cast ductile iron typically has a higher dimensional tolerance without the specific mold/metal reaction products in the skin region. The casting body and skin layer solidify with significantly different cooling rates in continuously cast iron.

OBJECTIVE

The objective of this study was the differentiation of the factors affecting machinability of ductile iron by comparison of surface and body machinability of castings from different metalcasting processes.

PROCEDURES

The procedures for this experiment were designed for 65-45-12 ductile iron to evaluate: i) the difference in the machinability of the skin and body of green sand castings and ii) compare the machinability of the body regions between green sand cast and continuously cast irons.

Two types of ductile iron castings were produced for the experiment, one from each of two industrial foundries. The first one was a continuously cast 8.2" diameter bar produced according to the production procedures of the foundry. This included charge melting in a coreless, line frequency induction furnace, holding in a channel induction furnace, tapping into a ladle at 2450F (1345°C) and a nodulizing treatment of 1.3% FeSi5Mg with inoculation using 0.7% Fe75Si. Table 1 presents the chemistry of the continuously cast ductile iron bar. The second iron was induction melted, treated in ladle by 1.5% FeSi5Mg, inoculated by 0.5% Fe75Si and poured into vertically-parted green sand molds from an automatic molding line. For the sand cast iron, the castings were test articles recommended by the American Foundry Society Cast Iron Division 5J (Committee for Machinability Studies), which are 10" diameter and 1" thick discs with a hub on one side.[9] The chemistry of the iron cast in green sand molds is also given in Table 1.

Table 1. Chemical Composition of Studied Ductile Irons (weight %)

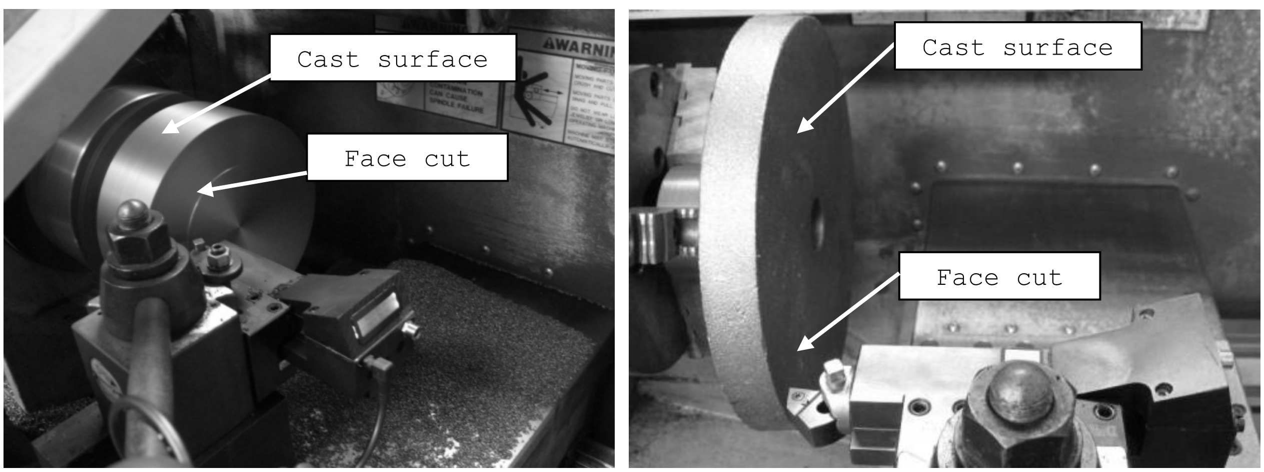
Iron Casting	C	Si	Mn	P	S	Cr	Al	Cu	Ti	Sn	Mg	N (ppm)
Continuous	3.6	2.5	0.3	0.01	0.01	0.03	0.01	0.03	0.01	0.006	0.05	40
Sand mold	3.8	2.4	0.3	0.02	0.003	0.04	0.015	0.2	0.006	0.008	0.035	55

Automated scanning electron microscopy with energy dispersive x-ray microscopy (SEM/EDS) image analysis (ASPEX system) was applied for the statistical evaluation of graphite nodules (nodule count and diameter). A 5 µm diameter was set as the lower threshold for what was counted as a nodule. An additional algorithm was applied for the evaluation of the spatial distribution of graphite nodules and also the average distance to each nodule's nearest neighboring nodule. Briefly, the precise two-dimensional coordinates of the center of each graphite nodule was used for the calculation of all distances between the selected particle and other particles. The minimum distance was used as the neighboring distance value and after that the selected particle was excluded from the set which allowed calculations to be continued for the next particle. Statgraphics software was used for the statistical evaluation of the gathered data.

Face cutting of continuously cast and sand-cast ductile irons was done on a computer numerically controlled (CNC) lathe (Figure 1) using a tool force dynamometer described by Richards, et al.[10] with a 1 Hz sampling rate at different cutting speeds (Table 2). All tests were performed during a 30-minute cutting period with no coolant. Compressed air was applied for the cooling of the dynamometer in order to prevent it from overheating. Inserts were tungsten-carbide with coatings applied by chemical vapor deposition [ZrC,N), Al_2O_3, and Ti(C,N)]. These tools were collected after each test for the measurement of flank wear using an SEM.

Table 2. Machining Parameters

Cutting speed sfpm	Feed inch per revolution	Depth of cut inches
100-300	0.006	0.03



a) ***b)***

Figure 1. Face machining with cutting tool force measurement: a) continuously cast bar and b) sand cast AFS Cast Iron Division disc.

The same machining sequences were applied for both the continuous and sand-cast ductile irons at the same cutting parameters (Table 2). These two casting methods provided a different orientation of the cast surfaces with respect to the surface used for face machining (Figure 1). In the case of sand cast article, the first face cut was taken along the casting skin. The reference (starting) plane for the first cut was defined using the CNC z-positioning of the tool tip. An average from six surface measurements along four lines 90 degrees apart was used to set the lathe's z-offset. Next, facing cuts were done in series with a constant depth of cut into the casting body. Three different tests were performed on the sand cast iron. In the first test, one article was sequentially cut from the skin to the body for evaluation of the effect of the skin region on cutting forces. In the second and third tests, tool wear was evaluated separately for the near-surface skin region and casting body, respectively. Skin machinability was evaluated by applying two cuts with 0.03" depth for five sand castings with total 30 minutes cutting time. A new tool insert was used for 30 minutes of sequential body cuts in the third test.

For the continuously cast bar the machining test was performed in the same sequences as were used for the sand castings, although during this test the surface being cut was perpendicular to the cast surface (Figure 1a). Machining of the continuously cast bar skin region only affected cutting forces at initial moments in each cut. The high dimensional tolerance and absence of mold/metal reaction products in the skin layer of the continuously cast bar caused the spike in cutting forces at starting moments of each cut to be insignificant.

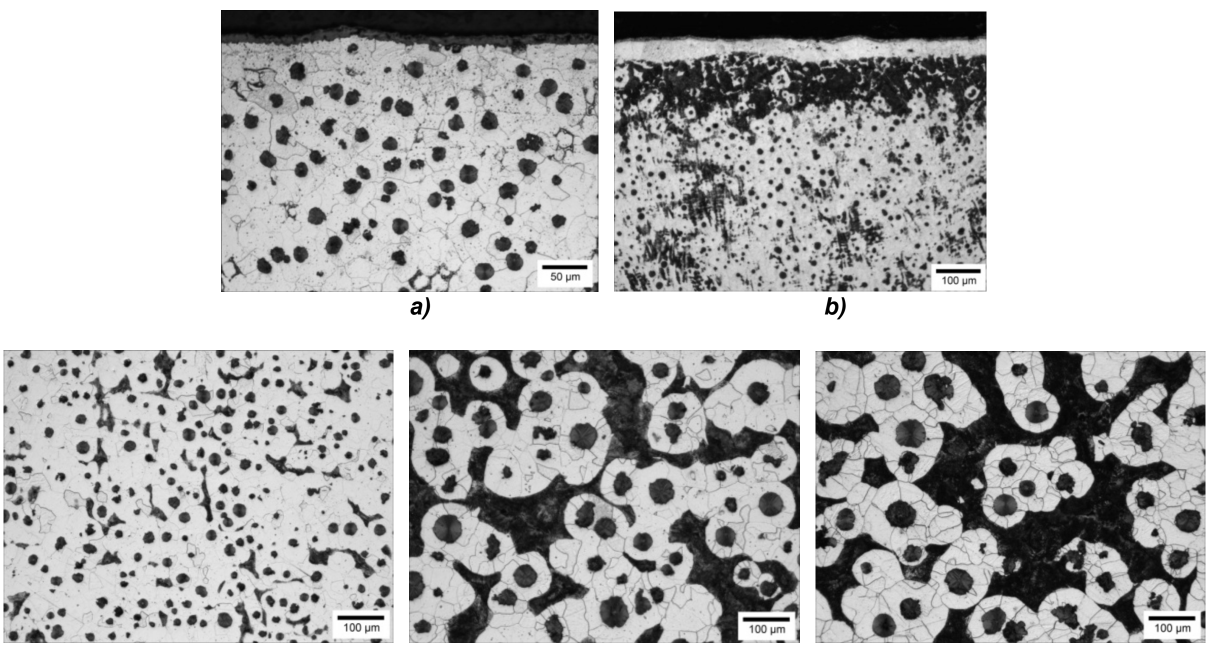
All data presented in this paper is for the naturally aged condition (20+ days) of the ductile irons studied, removing age strengthening as a variable. No further discussion of the age strengthening will be presented in this paper, but for more information on this topic see the paper by Richards, et al.[10]

RESULTS

MICROSTRUCTURE AND HARDNESS

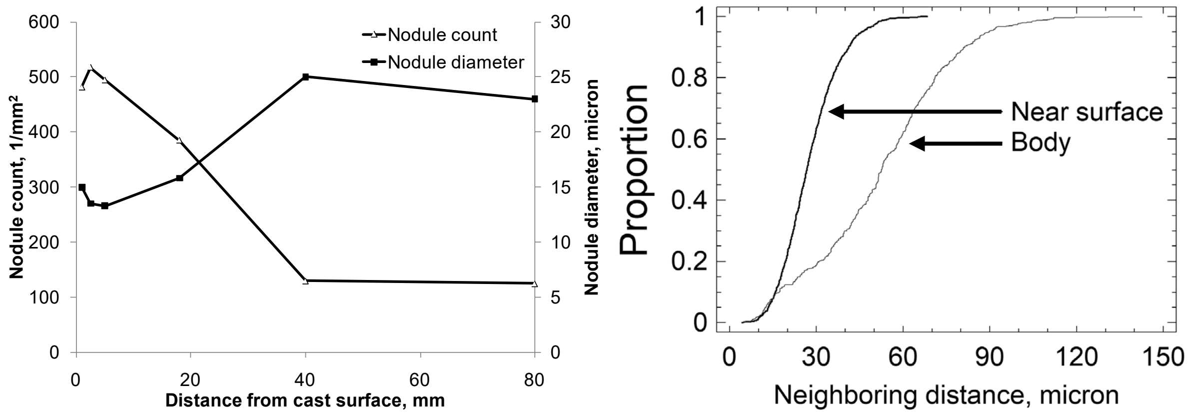
Continuously cast bar

The microstructure of the continuously cast bar (8.2" diameter) had features (Figure 2) that were the result of solidification and cooling conditions not typical in sand molds. A thin, near 50 µm, de-carburized layer within the skin region existed and was followed by a pearlite rim of approximately 70-100 µm depth. A mainly ferrite metal matrix and fine spherical nodules were beneath these skin features. Some amount of pearlite (3-7%) can be seen between where the original primary austenite dendrites were, which grew from the liquid in a direction perpendicular to the cast surface. With an increase in depth from 5 to ~25 mm, a significant decrease in graphite nodule count was observed. This factor strongly affects austenite decomposition kinetics pearlite content, despite a lower cooling rate.[11] Further examinations into the casting depth from 40 mm to the casting center (100 mm) did not show significant changes in the microstructure or hardness. More detailed information about the graphite structure was obtained using SEM quantitative analysis (Figure 3). The graphite neighboring distance is an important structural parameter which influences the fracture mechanics of heterogeneous materials and this parameter was significantly different between the skin layer and body region.



a) b) c) d) e)

Figure 2. Continuous cast bar surface: (a) 5-15 µm iron oxide film and (b) 20-30 µm de-carburized layer with additional pearlite rim. The microstructure of the casting body at (c) 10 mm, (d) 40 mm and (e) 80 mm from cast surface.

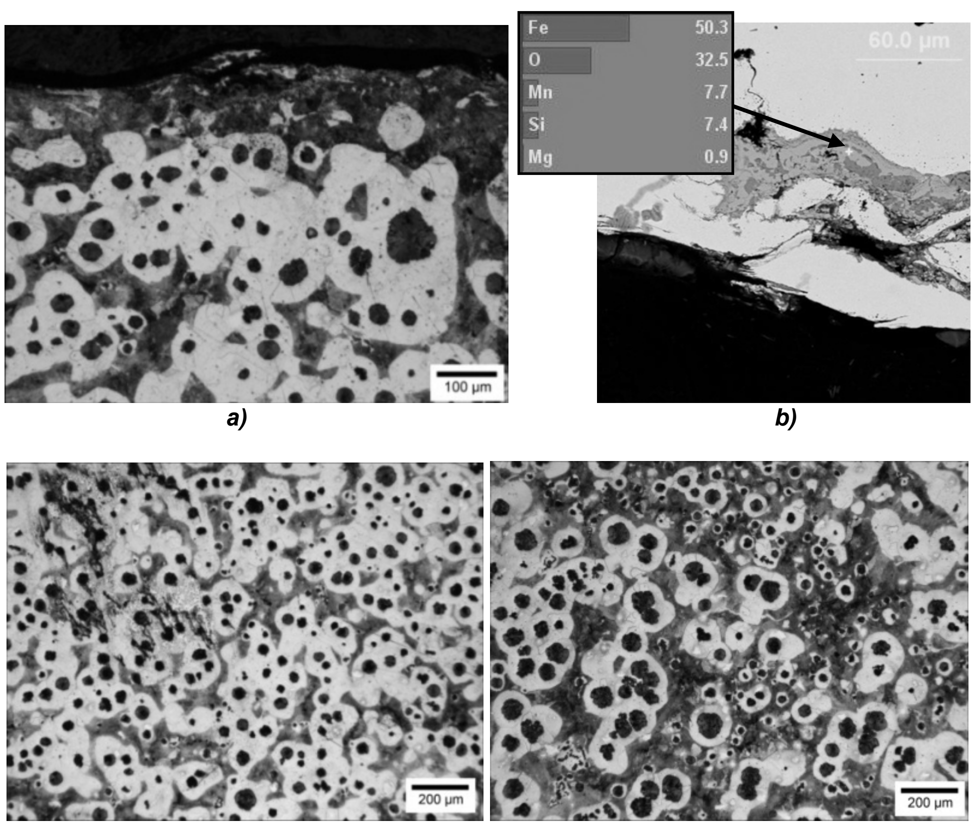


a) b)

Figure 3. (a) Graphite nodule count and nodule diameter of the continuously cast ductile iron versus distance from cast surface and (b) distribution of graphite nodule neighboring distance in the skin and body of the bar.

Sand castings

The microstructures in the skin and body regions of the sand cast test article are given in Figure 4. The cast skin surface contained a distinct layer of up to 100 µm depth which was comprised of significantly undercooled iron with incorporated films and large particles containing iron oxide and low melting temperature FeO-SiO2-MnO slag (Figure 4b,c). The skin layer had an increased nodule count in comparison to casting body that provided a lower average neighboring graphite nodule distance (Figure 5).



a) b) c) d)

Figure 4. Images of (a) skin region, (b) oxide film in skin region [60.0 µm bar], (c) 2 mm from cast surface, and (d) sand casting center. Images are optical except (b), which is SEM/EDS.

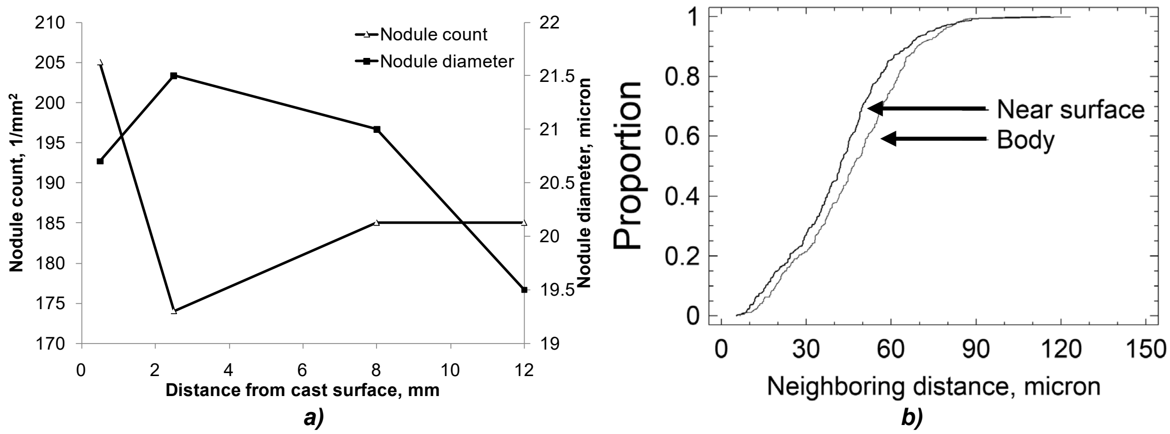


Figure 5. Sand cast ductile iron test article's (a) Graphite nodule count and diameter and (b) neighboring graphite nodule distance in skin layer and body.

MACHINABILITY TESTING

Continuously cast bar

Three-dimensional cutting forces (main, feed, and passive) from machining of the continuously cast ductile iron at different cutting speeds are shown in Figure 6. Feed force had a tendency to increase from the skin to the center of the bar and this difference was more pronounced at the high cutting speed. The higher dimensional tolerance of the cast cylindrical surface was apparent because there were little tool force fluctuations in the skin region. The chips formed by the cutting and tool flank wear are shown in Figure 7. Tool wear was not significantly influenced by increasing the cutting speed for the constant duration 30-minute test intervals. The maximum flank wear obtained was however at the highest cutting speed, 300 sfpm, and was 0.884 mm.

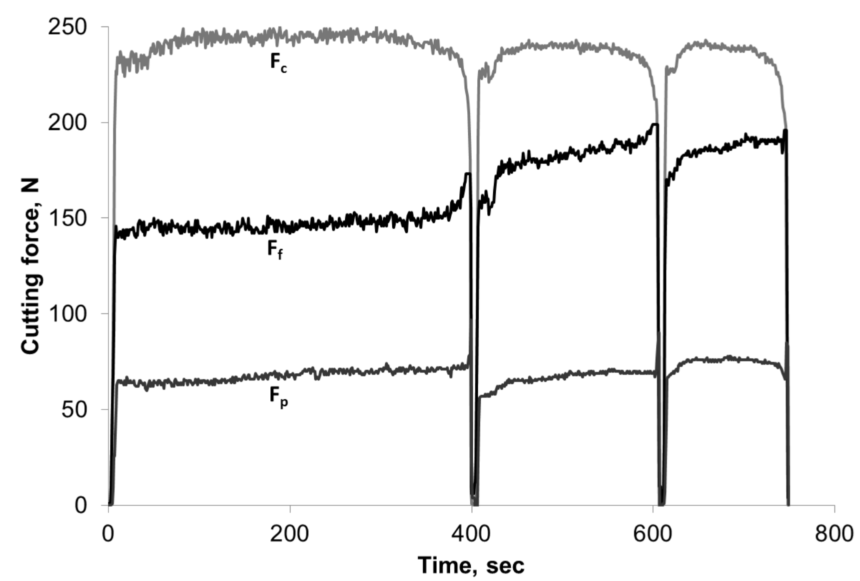


Figure 6. Cutting forces in three sequential face cuts of the continuous cast bar. Cuts at 100 sfpm (left), 200 sfpm (center), and 300 sfpm (right). The cuts start at the casting skin region and move to the center of the bar. The tool force nomenclature is: Fc = main (or cutting), Ff = feed, and Fp = passive.

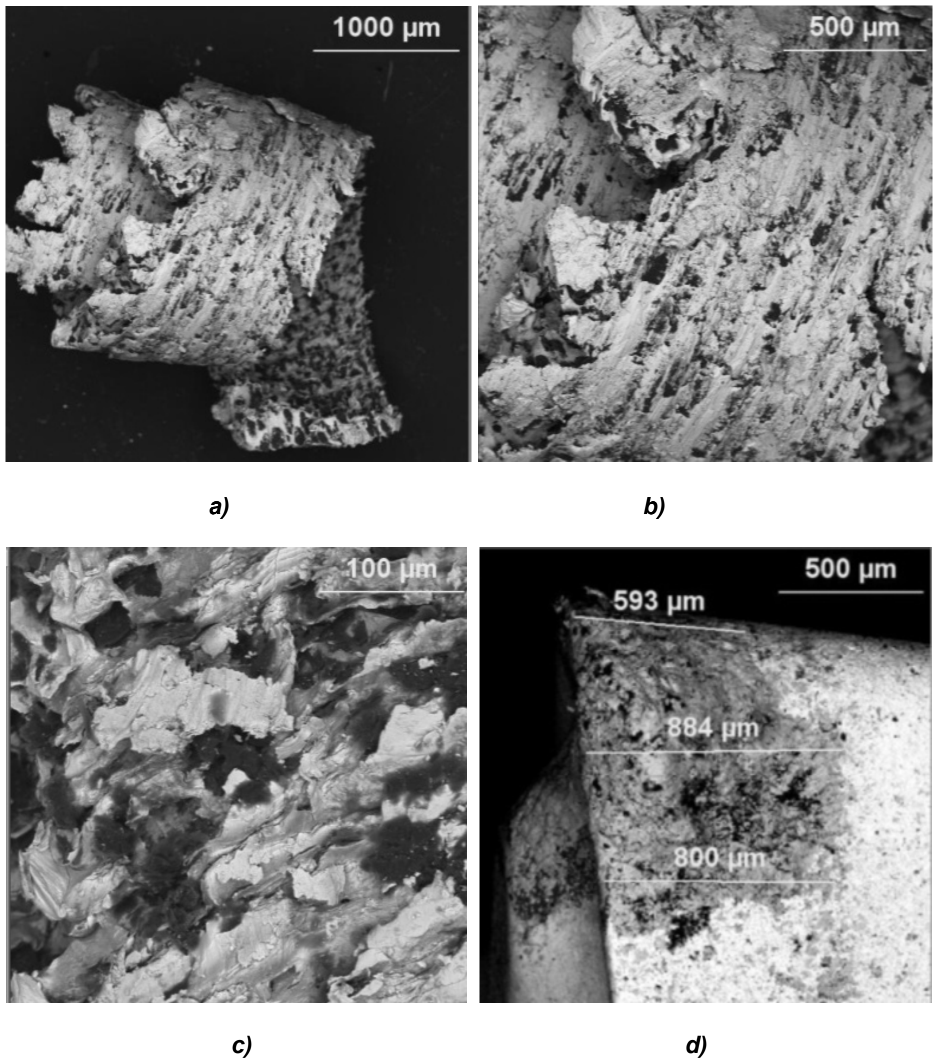
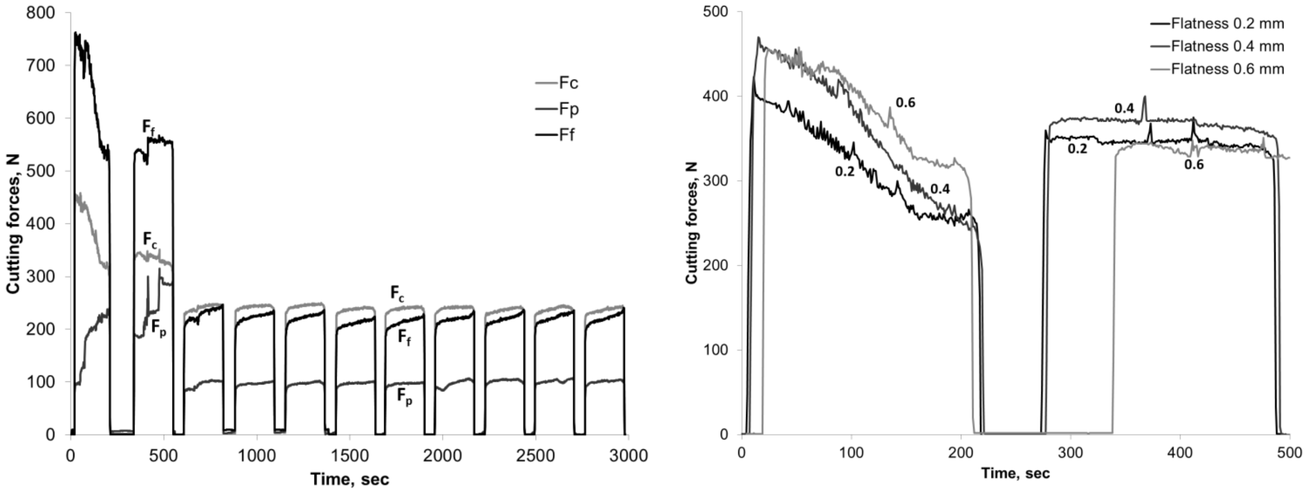


Figure 7. Images from an SEM of chips from the (a) side view, (b) external surface, and (c) internal surface and also (d) tool flank wear. Both imaged samples were from machining the continuously cast ductile iron at 300 sfpm for 30 minutes.

<u>Sand castings</u>

The surface geometry and microstructure of the skin region in the sand castings had a significant negative effect on its machinability. The first two cuts required larger cutting forces than any body cuts (Figure 8a). Both the sub-surface skin features and surface topology could have been responsible for this increase in cutting forces.

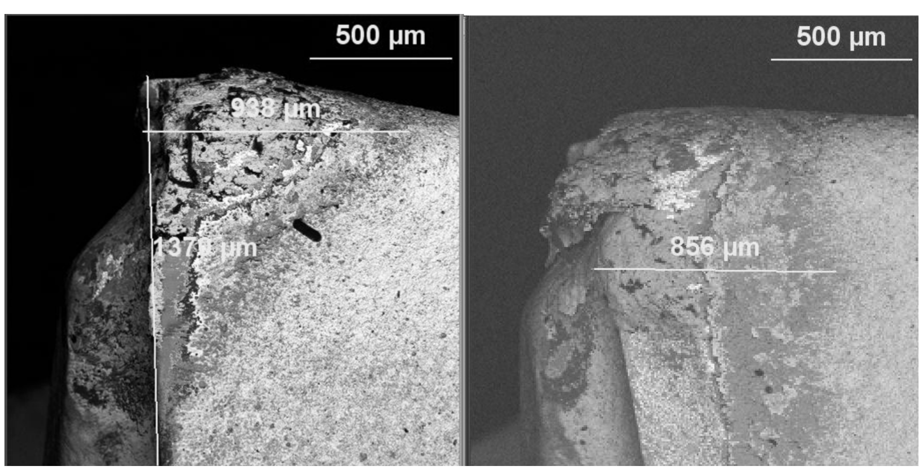
To verify these effects, three castings with different surface tolerances were machined. The effect of surface flatness variation (measured before each test directly on CNC) is shown in Figure 8b. An increasing variation in surface geometry increased fluctuations of cutting forces even though the average volume of removed material was approximately the same in each cut.



a) *b)*

Figure 8. The (a) cutting forces from surface cuts to body cuts of the sand cast article and (b) the effect of measured flatness variations on tool forces during the first two cuts at 300 sfpm is to increase the tool forces.

Tool wear was measured separately for the machining of the skin regions and the body of the sand castings. Two cuts from five castings, for a total of 10 cuts, were used in the testing of the skin regions. Five body cuts from two castings, for a total of 10 cuts were applied in the testing of the casting body machinability. For both sets of tests the time the spent machining was 30 minutes and the cutting speed was 300 sfpm. During the skin cuts, the tool insert possessed a large, abnormal wear crater and was partially broken in some tests (Figure 9a). Also, the tip of the tool had a build-up of ferrite (Figure 9b). All of these changes to the tool geometry increased cutting forces. For comparison, the tool insert used for 30 minutes of body cutting showed normal flank wear of a depth of ~0.54 mm. Figure 10 shows the structure of chips collected during cut 1 from both the skin region and the casting body. Chips from the skin region were significantly shorter with a larger degree of plastic deformation. It is noteworthy that a higher amount of plastic deformation requires more energy input, which can be exhibited as higher forces acting on the tool. Graphite nodules were not significantly exposed on the external surfaces of the chips. If graphite acts as a lubricant on the tool, then a relatively small area of exposed graphite would be expected to increase chip/tool interface friction. Body chips were longer and had exposed, deformed graphite particles on the external surfaces that worked as a lubricant on the tool surface.



a) *b)*

b)

Figure 9. For the tools used to machine the skin region of the sand cast ductile iron, there was: (a) abnormal tool wear with a broken edge [1370 µm vertical, 938 µm horizontal] and (b) a buildup of ferrite on the tool tip [856 µm]. Both tools were SEM imaged after 30 minutes of machining.

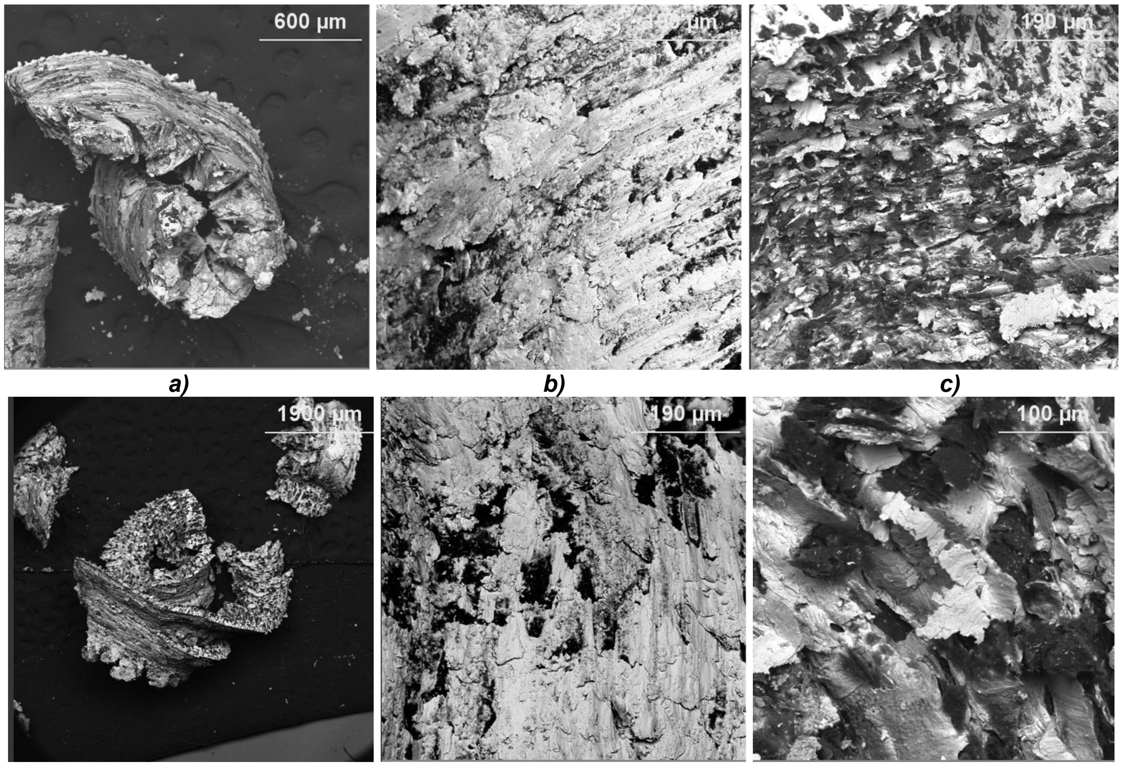


Figure 10. Chips formed during machining the skin region (a−c) and body (d−e) of ductile iron from sand molds (300 sfpm): (a, d) side view, (b, e) external surface, and (c, f) internal surface. [190 μm in b,c,e; 1900 μm in d; 100 μm in f]

DISCUSSION

In the sand castings, the cutting forces were higher when there was more variation in the flatness value (Figure 8b). A higher flatness variation indicates a less regular surface with more peaks and valleys, a surface with more slope to it, etc. A condition with higher flatness variation apparently creates a "hammering" effect of the workpiece on the tool, which increases averaged forces (Figure 8a) and can lead to premature tool failure. In addition to the flatness variation of the outermost skin surface, the skin region has differing machinability from the body region due to microstructure differences. The most pronounced case of this difference is in the castings from sand molds where the main cutting forces (Fc) in the skin region are around 150% of those in the body region. It should be noted that the hardness of the skin region is less than that of the body region, which shows that hardness alone does not determine cutting forces or machinability. Also, there were no large differences (Figure 5) in nodule count and a similar distribution of nearest neighboring nodule distances between the sub-skin (~ 2-8mm) and body regions. Thus, by a somewhat empirical process of elimination, the factors that control the distinction between tool forces encountered in the skin region and forces in the body region appear to be the surface topology with some likely influence of features just below the casting skin (Figure 4b). The continuously cast bar can also be considered, which will have a much smoother, even surface as a result of the casting process. This casting showed less variation of skin and body forces during the tests. From these comparisons, the general result made is that the surface topology (flatness) and non-metallic inclusions were the dominant variables controlling tool forces. This result does not mean variables such as nodule count and regional hardness (Figure 11) do not have some effect on machinability. The results indicate for the ductile irons studied, under the machining conditions used, the skin flatness was the most important factor.

The prime factor influencing cutting forces in the body region of the casting appeared to be the neighboring graphite nodules' distance (Figure 12). This parameter (L) affects cutting forces in two aspects. First, neighboring nodules' distance affects the transport of carbon atoms from the austenite metal matrix to the graphite nodules during the eutectoid reaction. Increasing the distance between nodules will increase pearlite content, and vice-versa. For the skin region, a short distance between nodules allows for lower pearlite content, despite a greater cooling rate. Second, the energy of crack propagation during shear is decreased by a lower average neighboring nodule distance. Theoretically, the crack propagation energy increases with the square root of distance between inclusions for plane strain. In general, a structure of ductile iron which has been made finer by inoculation or cooling rate required less energy for chip formation and thus, decreased cutting forces.

Experimental data (Figure 13) supported this statement: the body of the sand casting had a more refined graphite nodule structure than the body of continuously cast bar and required less cutting energy at the same machining parameters.

Figure 14 presents a plot of Log(F) versus Log(L) for body cuts of the continuously cast bar. An increase the average distance of graphite nodule neighbors distinctly had an influence on cutting forces in these experiments.

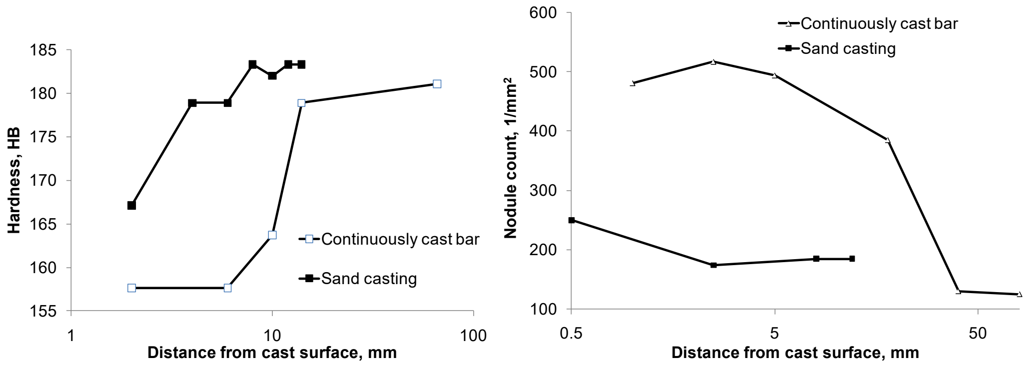


Figure 11. Comparisons of graphite nodule count and (a) hardness, and (b) distributions in continuously cast bars and sand cast ductile irons.

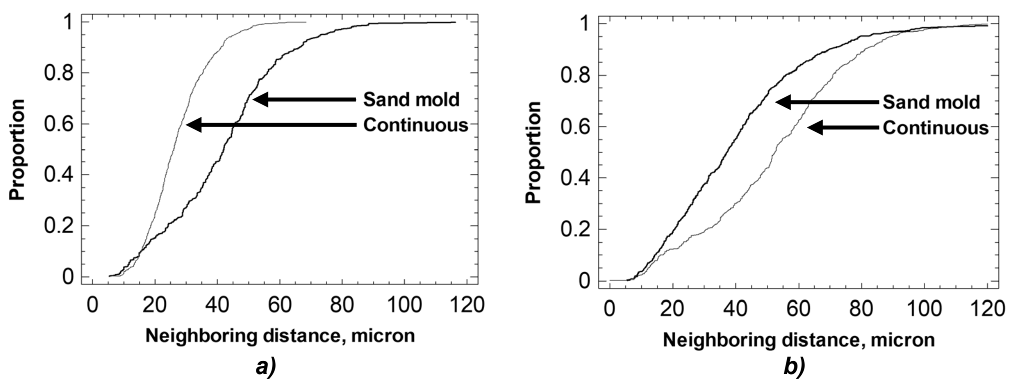


Figure 12. Comparison of graphite nodules neighboring distances in continuously cast bar and sand cast article: a) skin regions and b) center of castings.

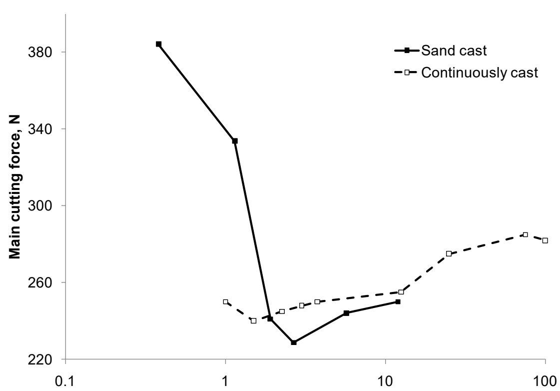


Figure 13. Comparison of main cutting force versus distance from cast surface for ductile iron from sand mold test article and continuously cast bar.

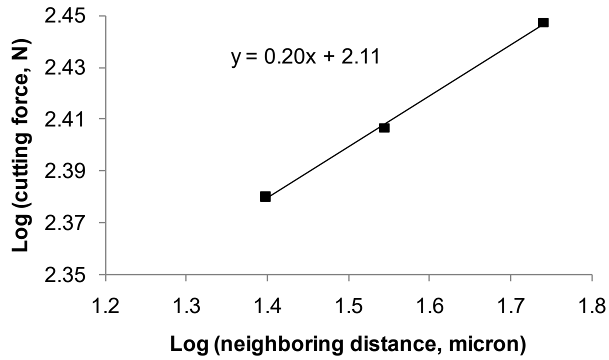


Figure 14. Effect of averaged graphite nodule's neighboring distance on cutting forces in continuously cast ductile iron.

Total separation of the specific effect of the individual variables (e.g., nodule count, diameter, nearest neighbor distance, and pearlite/ferrite ratio) was not possible in these experiments because, in moving from the skin to the body of the castings, variables can change simultaneously. For instance, the distance between graphite nodules did not appear to be an important factor in the hardness change of the sand castings (Figure 11). It can be seen that the distribution for the nodule neighbor distance in the sand castings changes little from the skin to the body, however, the hardness does. Unlike from the observations in sand casting, the greater differences in neighbor distance in the continuously cast bar when comparing skin and body could correlate to the hardness change. The nodules in the body of the continuously cast bar are apparently farther apart than at the surface, which promotes slightly higher pearlite content during casting cooling and this pearlite content manifested as a higher hardness reading. In general, the diameter of castings would be expected to primarily affect machinability by affecting the cooling rate and in turn affecting the nodule spacing/size and ferrite/pearlite ratio.

For reference, Table 3 summarizes much of the machinability data gathered for this paper.

Table 3. Comparison of Surface and Body Machinability of Continuously and Green Sand Mold Cast 45-12 Grade Ductile Irons at the Same Machining Parameters

Parameter	Continuously cast		Sand cast	
	Surface layer	Body	Surface layer	Body
Depth, mm	5-15	-	0.5-2	-
Hardness	155-160	180-185	165-175	185-190
Main cutting force	220-250	260-280	350-450	240-250
Tool wear (30 min test, 300 sfpm)	880		Abnormal wear and broken edge	550

CONCLUSIONS

The topology of the skin region and the microstructure features in this region are highly important for machinability of ductile iron castings produced in sand molds.

For the body region of castings, the distance between graphite nodules can be a key factor in overall machinability, with smaller distances giving better machinability.

Continuously cast 45-12 grade ductile iron may provide better machinability in the cast skin region and slightly less in the body region, when compared to sand cast ductile iron.

Sand cast 45-12 grade ductile iron may provide better machinability in machining performed after removal of the skin region, or potentially better machinability if the volume of the skin region being removed is much less than the volume of body region being removed. The latter case may be obtainable with large depths of cut; however, a larger depth of cut may introduce other issues with machinability not studied in this work.

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