SUMMARY REPORT

Project Title: Machinable, Thin-Walled, Gray and Ductile Iron Casting Production, Phase III

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Abstract:

This report presents the results of research conducted to determine the effects of normal and abnormal processing and compositional variations on machinability (tool wear rate) of gray and ductile iron. The procedures developed allow precise tool wear measurements to be made and interpreted in terms of microstructures and compositions. Accurate data allows the most efficient ways for improving machinability (without sacrificing properties) to be determined.

The ranking of materials has been found to be accurate and consistent no matter what machining operation or type of tool is used. Irons found to be hard to machine when being drilled were also found to be harder to machine in turning operations. Similarly, irons that produced higher tool wear rates with tungsten carbide (WC) inserts produced higher wear rates when silicon carbide (SiC) or alumina (Al_2O_3) inserts were used.

The effects of strength, hardness, matrix structure, and minor alloy concentrations are presented. Machinability was measured in both drilling and turning operations. Effects of micro-carbides and nitrides are noted.

This report is divided into four sections including (1) the task list and the work done to accomplish each task, (2) a technology report summarizing the techniques developed and technical results obtained, (3) conclusions drawn from the research, and (4) a milestone status table.

Project Tasks:

The research focused on (1) analyzing “easy” and “hard” to machine castings submitted by project participants, (2) conducting machinability experiments with both conventional and high performance tools, (3) conducting lathe and milling experiments to determine if the results were consistent with drilling data obtained in a previous study, (4) developing non-destructive techniques for estimating machinability, (5) developing a property database on selected irons, (6) evaluating resonance as a means of determining graphite shape in iron castings, and (7) transferring the technology to project participants.

Task Status:

Task 1. Advance machining technology by analyzing “hard-to-machine” and companion “easy-to-machine” castings.

Actions: Several factors have been found to degrade the machinability of both gray and ductile iron castings. The more important factors were (1) eutectic carbides in corners and fins of castings, (2) adhering sand not completely removed during the cleaning operation, (3) carbo-nitride compounds between titanium, vanadium, niobium, and tungsten contaminants in furnace charge materials, and (4) excessive amounts of iron carbides formed during the eutectoid transformation. Techniques were developed to identify these problems and eliminate these problems for sponsor companies.

Residual stresses introduced by thermal gradients and subsequent blast cleaning operations also degrade machinability. The solidification and cooling stresses are affected by gating system, shake out time, and casting geometry. Shot blasting the castings to remove adhering sand work-hardens the surface and introduces more residual stress. In 2002, procedures were developed for measuring both bulk and surface stresses. Bulk stresses were measured using a strain gauge technique, and surface stresses were measured using x-ray diffraction (XRD).

Task 2. Extend laboratory machining operations to higher performance tools including tungsten carbide, alumina, and silicon nitride.

Actions: Machining speeds have been increased from values in the range of 500-800 surface feet per minute (sf/min)(150-245 meters/minute (m/min)) normally used with tungsten carbide (WC) inserts to 1800 sf/min (550 m/min), which is above the commercial finishing range for tungsten carbide inserts. Three higher performance tools were evaluated including tungsten carbide coated with titanium nitride (TiN), alumina, silicon nitride (SiN), and cubic boron nitride (CBN).

Turning experiments were conducted using higher performance inserts on irons having different microstructures and machinability ratings. The compositions of two experimental ductile irons are presented in Table I.

Table I. Chemical Composition of Experimental Ductile Irons 13A and 21B

Material	C	Si	P	S	Ni	Cu	Sn	Mg	Cr	Mn	Ti
13A	3.62	2.63	0.020	0.0030	0.013	0.215	0.003	0.032	0.025	0.168	0.018
21B	3.41	2.69	0.017	0.0045	0.016	0.198	0.003	0.029	0.028	0.159	0.015

Machinability experiments were conducted on the “easy-to-machine” with WC, TiN coated WC, and alumina at two surface speeds, 600 and 1800 sf/min (185-245 M/min). The results are illustrated in Figure 1. The wear rate is the slope of the tool wear curve and is reported in mils (0.001 inches, (0.025 mm) per 100 in³ (1640 cm³) of metal removed.

Fig. 1. Flank tool wear rate produced by different cutting tool on ductile iron 21B.

The two WC tools had wear rates near zero at 600 f/min (185m/min). The alumina exhibited a wear rate of about 90 mils (2.25mm) per 100 in³ (1640 cm³) of metal removed, probably because the tools chipped at the low surface speeds and low tool temperatures involved. The wear rates at the higher turning speed of 1800 sf/min (550 M/min) were 423, 387, and 147 mils/100in³ (10.7, 9.8, and 3.73 mm/1640 cm³) for the TiN coated WC, WC, and alumina, respectively. There was no statistical difference in the wear rates between the WC and TiN coated WC tools, but the wear rate was lower with the alumina insert at higher speeds and tool tip temperatures, as expected.

Similar data on a less machinable ductile iron, Material 13A, is illustrated in Figure 2. The flank wear rate at 600 f/min (185m/min) was about 50 mils per 100 in³ (1.27 mm per 1640 cm³) of metal removed for all three tools. The tool wear rates at 1800 sf/min (550 m/min) were higher, with values of 1239, 1169, and 212 mils/100in³ (31.4, 29.6 and 5.38 mm/1640 cm³) for the WC, TiN coated WC, and alumina inserts, respectively. The differences in wear rate between the WC and TiN coated WC were not statistically significant, but the wear rate of the alumina tool was substantially lower.

The more difficult to machine 13A material produced a higher wear rates at 600 and 1800 sf/min, (185 and 245 m/min) in all tools, compared to material 21A but the machinability ranking stayed the same. Material 21B produced lower tool wear rates, and material 13A produced higher tool wear rates at both speeds examined.

Fig. 2. Flank tool wear rate produced by different cutting tool on ductile iron 13A.

The metallurgical structure of the material being machined is very important. A higher performance and more expensive tool may allow more castings to be machined before making an insert change, but the metallurgical features that cause higher wear rates with WC tools also cause higher wear rates in other harder and more expensive tools.

Similar behavior was found when comparing tool wear rates obtained with WC and SiN inserts.

Task 3. Extend machining studies to turning operations.

Actions: A CNC lathe and a CNC milling machine were configured for turning experiments, and the results obtained were compared with results obtained in a previous study where drilling experiments were conducted on the same materials.

The tool wear rates obtained with two gray irons having the compositions presented in Table II were determined. The castings were produced as plates with dimensions of 12 in. (300 mm) long, 8 in. (200 mm) wide, and 2 in. (50 mm) thick.

Table II. Chemical Composition of Experimental Gray Iron G8-6-2 and G8-7-2

Material	C	Si	P	S	Ni	Cu	Sn	Mo	Cr	Ti
G8-6-2	3.16	2.02	0.020	0.071	0.06	0.685	0.085	0.029	0.155	0.011
G8-7-2	3.17	2.01	0.022	0.070	0.06	0.690	0.015	0.029	0.160	0.011

Drillability experiments were conducted using 0.25" (6 mm) diameter, high speed steel (HSS) drills. Each drill was used until it "squealed". Drilling a few more holes past "squeal" resulted in welding of the drill to the plate.

Drilling experiments were conducted at speeds of 85, 98, and 118 sf/min (25, 30, and 36 m/min), and triplicate tests were performed at each speed. All experiments were conducted at a feed rate of 0.009 in (0.225 mm) per revolution. Holes were drilled on half inch centers (12.7 mm) or one drill diameter apart to avoid strain hardening effects.

Turning experiments were performed on the same materials using WC inserts. The cutting depth was 0.030 in. (0.75 mm), and a feed rate was 0.003 in. (0.075 mm) per revolution. Experiments were conducted at machining speeds of 450, 550, and 650 sf/min (135, 167, and 200 m/min), well above the speeds used with the high speed drills, and triplicate experiments were conducted under each condition.

Tool wear was measured on all drills and inserts as a function of the volume of metal removed. Tool wear experiments were continued until the tool flank developed a maximum wear of about 0.04 in. (1 mm). Tool wear data obtained in drilling experiments at speeds of about 100 sf/min and turning experiments at speeds of 450 to 650 f/min (135 to 167 m/min) are illustrated in Figure 3.

Fig. 3. Machinability data on two gray irons using drilling and turning operations at different surface speeds.

The material ranking, as measured by the volume of metal removed before reaching the specified flank wear criteria, was the same whether metal removal was by drilling or turning. Material designated as G8-7-2 was more machinable than iron G8-6-2 in drilling operations at speeds of 80 to 100 f/min (25 to 30m/min) in turning operations at speeds of 450 to 650 sf/min (135 to 200 m/min). This again indicates that metallurgical characteristics significantly affect the

rate of tool wear regardless of the type of machining operation. The data also clearly shows that higher machining speeds increase the tool wear rate, undoubtedly because the tool tip reaches higher temperatures at higher speeds, irrespective of the type of tool or insert used.

The volume of metal that may be removed with a particular tool may change with tool material, geometry, and cutting conditions, but the material ranking has not been found to change with either machining speed or tool material.

Task 4. Develop nondestructive procedures that can anticipate machinability of castings.

Actions: Procedures were developed for measuring density and ultrasonic velocity and the results were correlated to machinability.

A wide variety of gray and ductile irons from production foundries were examined. The chemical composition, total carbon, free carbon, and bulk density of each material was determined, the machinability evaluated, and correlations developed. The density was found to be a function of graphitic carbon and silicon concentrations. From density and silicon concentration, the volume fraction of graphite was calculated using the following equation

$$V_v = 100 - \frac{51.2 + 6.3\rho_1 + 0.35W_{si}}{7.74 - 0.0556W_{si}} \rho_1$$

Equation 1

Where:

V_v is volume fraction of graphite, %

ρ_1 is bulk density of cast iron sample, g/cm³

W_{si} is weight percent of silicon content in the test sample, %

Fig. 4. Correlation between graphite volume fraction calculated from density and analytically determined free carbon in gray and ductile iron.

The graphite volume fraction calculated using this equation is illustrated in Figure 4 as a function of free carbon obtained by chemical analysis. The free carbon content ranged from near 0 to about 3.6% by weight and from about 0 to about 11% by volume. The linear correlation coefficient (R^2) between graphite volume (from free carbon measurements) and volume calculated from the density measurements was 0.94. The graphite volume calculations made from density measurements agreed with, and were more precise, than results obtained using metallographic techniques.

Graphite is an important microstructural feature affecting machinability. Accurate measurements of density and graphite volume fraction provide a convenient method for predicting machinability.

The weight percent micro-carbides in iron can be determined from density, total carbon, and silicon concentrations using Equation 2.

$$W_{mc} = 15W_{tc} + 94.8\rho_I + 5.27W_{si} - 734\% \quad \text{Equation 2}$$

Where:

W_{mc} is weight percent of microcarbides, %

W_{tc} is weight percent of carbon content, %

Micro-carbides affect machinability, with lower micro-carbide contents associated with better machinability. (Bates, 1996) A comparison of the micro-carbide content calculated from combined carbon measurements and calculated from density (Equation 2) is illustrated in Figure 5. The micro-carbide contents varied from 0 to about 16% with a linear correlation coefficient (R^2) of 0.8.

Fig. 5. Comparison of the micro-carbide contents calculated from combined carbon and density measurements.

Higher micro-carbide concentrations, especially above 12% by weight, significantly degrade machinability.

Task 5. Evaluate Resonance as a method for evaluating graphite structure in iron castings.

A Quasar Compensated Resonance (CRT) inspection instrument was purchased and used on a variety of compacted and gray iron castings to evaluate the ability of resonance to assess graphite shape. Resonance testing has been practiced for many years using a “ping and ring” procedure. A part is impacted and the quality of the ring examined by a microphone or “calibrated ear”. The “calibrated ear” may be someone with good audio acuity or an instrument that determines either the fundamental resonant frequency or the rate of sound decay (ring down or Q factor).

Parts can resonate in flexure, tension, torsion, and volumetrically. The resonance frequencies are functions of the material modulus, geometric stiffness of the part, and the presence of material or part anomalies. Since graphite shape and volume affects material modulus, higher carbon concentrations decrease resonance frequencies for a particular graphite shape factor. More compacted graphite shapes increase resonance frequencies at a particular carbon equivalent.

The Quasar instrument has one transducer that vibrates parts over a frequency range and two transducers that detect resonances. Parts are usually driven through a frequency range, twenty or more resonance peaks located, and the part evaluated for consistency based on a comparison of the spectrum of parts being examined with spectra obtained from other parts considered to be acceptable.

Fig. 6. Resonance frequency spectrum of four cylinder liner castings.

Cylinder liner castings were evaluated for nodularity using the Quasar unit. The objective was to determine if the resonance could be used to determine the nodularity of compacted graphite irons and the technology used to sort castings. Typical resonance spectra from 13.124 to 20.123 KHz are illustrated in Figure 6.

Resonance peaks 1, 2, 3, and 4, as labeled in Figure 6, clearly separate the CG iron castings numbered 418 and 428 from flake graphitic castings, but additional research and castings are needed to demonstrate that the unit will identify and reject castings with an excessively high nodularity.

Task 6. Develop room temperature properties on selected irons for design purposes.

Actions: Tensile, compression, and precision elastic limit specimens were designed for making property measurements. However, the American Foundry Society obtained funding for a separate project to develop design data. This task would duplicate the AFS task and detract from the machining study. Approval to redirect the funds to residual stress effects was approved at the sponsor meeting held January 24, 2002.

Task 7. Transfer improved machining technology to participants through plant trials, demonstrations, seminars and publications.

Actions: This task was conducted by holding technology reviews on approximately four month intervals throughout the project. Verbal presentations were made to project participants and experiments devised to conduct in participating foundries to evaluate the technology developed and determined methods for improving iron machinability.

EFFECTS OF MICROSTRUCTURE ON MACHINABILITY

In general, machining characteristics of metals are classified by the type of chip formed. Terms such as "continuous," "discontinuous," and "discontinuous with built-up-edge" are commonly used. Most metals exhibit reasonably predictable machinability based on well-founded cutting theories (Ernst, 1938, Merchant, 1945, Pispanen, 1937, and Shaw, 1986).

Many factors can influence tool wear rate and tool life. In iron, these factors include graphite size and distribution, silicon content, ferrite content, cooling rate from the eutectic through the eutectoid temperatures, and the presence of carbide, oxide, and nitride inclusions. Steel machinability is affected by strength, hardness, and type and number of inclusions distributed throughout the matrix. Generally sulfides improve machinability, and both deoxidation and reoxidation products degrade tool life. The following section describes the procedures used and some results obtained illustrating the effects of microstructural variables on machinability.

Effects of Microstructure on Machinability Measured in Drilling Operations

Drilling experiments were conducted to determine the effects of microstructure on drillability. The tool wear rate was determined by measuring the flank wear on 0.25 inch (6 mm) diameter, M7 high speed steel (HSS) drills. Castings were produced commercially and supplied in the

form of 8 by 12 inch (200 by 300 mm) plates having a thickness of either one or two inches (25.4 or 51 mm). Successive holes were drilled until either the drill “squealed” or 720 holes were drilled with a single drill.

Wear measurements were made after drilling the first and second hole and then at various intervals depending on the rate of tool wear. Wear measurements were usually made at three speeds, and triplicate experiments were performed at each speed. All experiments were conducted at a feed rate of 0.009 in (0.225 mm) per revolution and on a CNC vertical milling machine. Holes were drilled on half inch centers (12.7 mm or one drill diameter apart) to avoid strain hardening effects.

Effects of Microstructure on Machinability Measured in Turning Operations

Three-quarter inch (19 mm) square, un-coated fine-grained tungsten carbide (SPG631) inserts were used to evaluate the effects of metallurgical variables on tool wear during turning operations. The tool flank showed progressively more wear as it was used to remove more metal from castings. The area and shape of the wear land on each insert edge was periodically recorded by removing the tool from the lathe and digitally recording the wear pattern. The rate of flank wear was determined as a function of the microstructure and the volume of material removed.

Experiments were performed at three speeds, usually in the range of 600 to 1200 f/min (185 to 365 m/min), with a feed rate of 0.003 inches (0.0076 mm) per revolution and a depth of cut of 0.030 inches (0.76 mm). A schematic of a worn insert is shown in Figure 7, and typical flank wear patterns on successive passes are illustrated in Figure 8.

Fig. 7. Schematic illustration of flank wear on an insert. A. Depth of Cut, B. Maximum Wear Height, C. Average Wear.

Fig. 8. Progressive tool flank wear on an insert.

A typical tool wear curve obtained at a turning speed of 1050 sf/min (320m/min) is illustrated in Figure 9. The solid line through the data represents the best linear fit between the flank wear and the volume of metal removed. The dashed lines on either side of the solid line represent one standard deviation in the tool wear data.

Fig. 9. Average flank wear as a function of material removed at 1050 sf/min (320m/min) from ductile iron.

Tool wear data obtained under specific conditions are summarized in the boxes on each graph. The data includes the volume of metal removed before reaching an average flank wear of 6.5 mils (1.65 mm) and the least squares linear slope of the wear curve. The data obtained with each insert edge is plotted with a different symbol so the wear on any insert can be followed if desired.

The tool wear curves generally show some initial “break-in” wear followed by steady state wear. The initial wear occurred as the tool tip was abraded and perhaps somewhat rounded. The linear wear region is a function of the cutting speed and the characteristics of the material being machined.

Isolating Microstructural Effects on Machinability

Copper and tin concentrations in ductile iron were varied to produce a full factorial designed experiment (DOE) to provide data on the effects of matrix micro-structure on tool wear during drilling. The materials evaluated included (1) castings with a low copper and low tin

concentration, (2) castings having a higher copper and a low tin concentration, (3) castings having a low copper and a higher tin concentration, and (4) castings containing relatively high copper and high tin concentrations.

Copper concentrations were varied between 0.08 and 0.5 wt %, and tin concentrations were varied between 0.005 and 0.1 wt %. The actual compositions of the alloys are presented in Table III. The base iron composition was constant with the exception of the silicon at 2.6 wt% in the low copper-low tin alloy and 2.99 wt% in the high copper and low tin alloy.

Table III. Compositions of Materials Used in Drilling Experiments (wt %)

Alloy	D10-1	D10-2	D10-3	D10-4
C	3.6	3.65	3.58	3.57
Si	2.57	2.99	2.78	2.78
C.E.	4.24	4.39	4.28	4.27
Ni	0.04	0.02	0.02	0.02
Cu	0.08	0.38	0.06	0.51
Sn	0.005	0.005	0.099	0.097
Sb	0.003	0.003	0.003	0.003
Mg	0.039	0.038	0.032	0.04
Cr	0.04	0.03	0.03	0.03
Mn	0.19	0.2	0.2	0.2
Ti	0.01	0.007	0.007	0.007

Five ductile irons were to characterize the effects of microstructure on tool wear rates in turning experiments, and their chemical compositions are presented in Table IV. The carbon concentrations were in the range of 3.75 to 3.90%, and the silicon varied from about 2.5 to 2.7%. D1 had lower Mn (0.27 wt %) and Cu (0.06 wt %) but higher Sn (0.035 wt %) than D3.

Table IV. Compositions of Materials Used in Turning Experiments

Alloy	D1	D2	D3	D4	D5
C (w %)	3.75	3.82	3.80	3.90	3.90
Si (w %)	2.57	2.55	2.69	2.49	2.49
C.E.	4.39	4.46	4.47	4.52	4.52
Mn (w %)	0.27	0.22	0.36	0.23	0.23
Cu (w %)	0.06	0.03	0.24	0.03	0.03
Sn (w %)	0.035	0.008	0.008	0.007	0.008

Materials Characterization

Brinell hardness measurements, tensile properties, and microstructural characteristics were determined on each material. Three samples were removed from each material for tensile evaluations, and the full tensile stress-strain curves were recorded.

All Brinell hardness measurements were made using a 3000 kg load after sections removed from the castings had been ground to produce plane and parallel surfaces at least 0.75 inches (20mm) thick. From 5 to 30 measurements were made on castings to determine the hardness range and average hardness.

Automated microstructural image analyses were conducted at 200x with Image Pro Plus© to determine the nodule counts. Nodules or particles smaller than 6 microns in diameter were discarded. Manual measurements were made to determine the amount of ferrite and pearlite in the matrix using a 60 point grid.

Each microstructure was evaluated after etching representative samples with Nital (4% nitric acid in methanol) and examining at 200X. The metallurgical characteristics were usually determined at the casting mid-radius or quarter thickness.

Statistical Analysis

(ANOVA) statistical analyses were conducted using Stat-Graphics© to examine the significance of the effects of strength, microstructure, and nodule count on machinability. Regression analyses were conducted using both the p-value and the R^2 statistic to evaluate correlations between properties, microstructural and machinability.

The p-value is the probability that the correlation found is not associated with random variations in the data. P-values greater or equal to 95% are considered to be significant. The R^2 statistic provides a measure of how much of the variation in a dependent variable can be explained by the variations in the independent variable. In a multi-variant analysis, R^2 values less than about 25% are considered to be weak; values ranging from about 25% to 55% are considered to be moderate; and values above 55% are considered to be strong.

RESULTS AND DISCUSSION – DRILLING

The metal volume removed before drill failure is plotted as a function of machining speed in Figure 10, and the volume of metal that could be removed decreased as the machining speed increased. Also, the metal volume that could be removed before tool failure decreased as the material strength increased. The slope of the metal volume removed curve vs. tool speed was relatively flat in material D10-1 having a yield of 47 ksi (324 MPa). However, the slope increased as the yield strength increased.

Data on the number of holes that could be drilled before squeal at 85 f/min (26 m/min) is summarized in Table V. The best machinability was found in the alloy with low copper and tin concentrations having the lowest strength. All three drills were still operating after drilling 720 holes. A significant reduction in the number of holes that could be drilled before drill squeal occurred in alloys with higher copper and low tin concentrations and with higher strength alloys.

The average number of holes drilled at 85 f/min (26 m/min) before squeal was 87 in the alloy containing 0.38% Cu and 0.005 Sn, and decreased to 60 in castings containing 0.06% copper and 0.099% tin. Only five holes could be drilled in the high copper, high Sn material containing 0.51% copper and 0.097% Sn and having the highest strength.

Fig. 10. Volume of metal removed before squeal as a function of drilling speed.

Table V. Number of Holes Drilled before Squeal at 85 f/min (26m/min)

Alloy Code	Cu	Sn	Average	Std. Dev.
D10-1	Low	Low	720	0
D10-2	High	Low	87	11
D10-3	Low	High	60	16
D10-4	High	High	5	1

Brinell hardness data is summarized in Table VI. The average Brinell hardness was 161 BHN in the alloy with low copper and tin concentrations, 222 in the alloy with high copper and low tin concentration, 270 in the alloy with low copper and high tin, and 295 in the alloy containing the highest copper and tin concentration.

Table VI. Brinell hardness (3000 kg) of Ductile Iron Castings

Alloy Code	Cu	Sn	N	Average	Std. Dev.
D10-1	Low	Low	45	161	1.6
D10-2	High	Low	30	222	8
D10-3	Low	High	30	270	4.3
D10-4	High	High	30	295	4.9

The relationship between Brinell hardness and the number of holes drilled before squeal at a speed of 85 f/min is illustrated in Figure 11. The probability of statistical significance was 100%, and the R^2 statistic was 87% using an exponential fit.

The yield strength of the experimental castings ranged from 48 ksi (330 MPa) in the alloy with low copper and tin concentrations to 75 ksi (515 MPa) in the alloy with the highest high copper

and tin concentration, as shown in Table VII. There was a good correlation between yield and machinability as illustrated in Figure 12. The R^2 statistic for the correlation was 91% using an exponential fit.

Fig. 11. Effect of Brinell hardness on the number of holes drilled before squeal at 85 f/min (2626 m/min). The error bars are the 95% confidence interval.

Table VII. Yield Strength (ksi) of Ductile Iron Drill Plates

Alloy Code	Cu	Sn	N	Average YS	Std. Dev.
D10-1	Low	Low	3	47.6	1.6
D10-2	High	Low	3	57.8	1.6
D10-3	Low	High	3	67.8	1.9
D10-4	High	High	3	75.0	0.5

Similar R^2 values were obtained for the correlations between Brinell hardness. The variation in mechanical properties and machinability was related primarily to the changes in ferrite.

The ferrite content of the castings is summarized in Table VIII. Ferrite ranged from 72% in the irons having low copper and tin concentrations to almost 0 in irons with the highest copper and tin concentrations. The correlation between wear rate and ferrite is illustrated in Figure 13, and the relationship between ferrite and yield strength is illustrated in Figure 14. The fit to the data was almost 100%.

Table VIII. Volume Percent Ferrite of Ductile Iron Castings

Alloy Code	Cu	Sn	N	Average	Std. Dev.
D10-1	Low	Low	20	72.42	8.2
D10-2	High	Low	20	44.42	9.15
D10-3	Low	High	39	17.14	6.29
D10-4	High	High	20	0.17	0.52

Fig. 12. Correlation between yield strength and drillability at 85 f/min (26m/min). Error bars are the 95% confidence interval.

Fig. 13. Effect of ferrite on the number holes drilled before squeal. The error bars are the 95% confidence interval.

The nodule density ranged from about 100/mm² to 160/mm² in these irons. While high nodule counts usually improve machinability, there was no effect in the range covered in these irons.

ANOVA results relating the copper and tin concentration to the drillability at 85 f/min (26 m/min) are presented in Table IX. The copper and tin concentrations and interactions between the two

contributed significantly to the drillability. Copper variations explained about 35% of the variability, tin about 41% of the data, and combination effects explained 21% of the variability. Taken together, these variables explained 97% of the tool life variability.

Fig. 14. Effect of ferrite on yield strength of ductile iron. The error bars are the 95% confidence interval.

Table IX. ANOVA Statistics for Holes to Squeal at 85 f/min (26 m/min)

	Source	Sum of Squares	P-Value	Contribution to Total Variation
Main Effects	Cu	355008	100%	35%
	Sn	413665	100%	41%
Interactions	Cu and Sn	249985	100%	21%
	Residual	745		
	Total	1019400		

Decreasing the copper concentration from about 0.45 wt% to 0.07 wt% increased the ferrite content and improved the machinability. Similarly, reducing the tin from about 0.1 to 0.005 wt% improved the machinability. At the concentrations examined, both copper and tin decreased machinability by similar amounts.

RESULTS AND DISCUSSION - TURNING

The volume of metal removed during turning before reaching a flank wear of 0.005 inches (0.127 mm) is illustrated in Figure 15. As expected, the tool life decreased with increasing machining speed. At a speed of 1050 sf/min (320 m/min), the volume of metal removed was

highest with material D2. The volume decreased in materials D4, D5, D3, and D1, and D1 contained the highest tin concentration (0.035 wt %).

Fig. 15. Effect of machining speed on volume of metal removed before 0.005 in. (0.127 mm) flank wear in several ductile irons.

The yield strength of each iron is also presented in Figure 15. D1 with the highest yield strength (60.5 Ksi, 450 MPa), had the lowest machinability. D3, with a slightly lower strength had improved machinability. D2, with the lowest yield strength of 49.5 ksi (340 MPa), had the best machinability. There was some inconsistency in the data on materials designated as D4 and D5 in relation to strength. D5, with a lower strength than D2, had worse machinability because it contained dispersed micro-carbides and micro-nitrides. D4 had yield strength similar to D2 but substantially lower machinability, again because of it contained dispersed carbides and nitrides in the microstructure.

The volume of metal that could be removed before reaching a flank wear of 6.5 mils (0.165 mm) at 1200 sf/min (365 m/min) is illustrated in Figure 16 as a function of yield strength. The R^2 statistic for a linear fit correlation was 86%. In general, machinability decreases with strength and with the presence of hard phases such as micro-carbides and nitrides.

The relationship between Brinell hardness and volume of metal removed before reaching 0.065 inches (0.165 mm) of flank wear is illustrated in Figure 17. Small dispersed hard inclusions produced variations in machinability at a comparable hardness. The R^2 statistic for the correlation was 84% using a linear fit. D1 had the highest Brinell hardness of about 225 and the worst machinability.

The ferrite content in these castings ranged from about 50% to 86%, and the metal volume removed at a flank wear of 6.5 mils (0.165 mm) at 1200 sf/min (365 m/min) as a function of ferrite is illustrated in Figure 18. The R^2 statistic for the correlation was 92% using a linear fit.

Fig. 16. Correlation between yield strength and metal removed before 0.065 in. (0.165 mm) flank wear at 1200 f/min (365 m/min). Error bars are 95% confidence interval.

Fig. 17. Correlation between Brinell hardness and metal removed before 0.065 in. (0.165 mm) flank wear at 1200 sf/min (365 M/min). Error bars are 95% confidence interval.

Fig. 18. Correlation between ferrite content and metal removed before 0.065 in. (0.165 mm) flank wear at 1200 sf/min (365 m/min). Error bars are 95% confidence interval.

The correlation between ferrite and yield strength in these alloys is illustrated in Figure 19. The R^2 statistic for the correlation was 94% using a linear fit.

Fig. 19. Effect of ferrite on yield strength of experimental ductile irons. Error bars are 95% confidence interval.

Practical Application – Brake Drums

Two sets of gray iron brake drum castings were recently submitted for analysis. The castings were produced by two foundries and are referred to as 102-1-A and 102-1-B. The casting had a maximum OD of 19 inches (483 mm) and a height of 8.5 inches (216 mm). A section was removed from the rim of each casting, as illustrated in Figure 20, for determining the composition, density, ultrasonic velocity, and microstructure. The rim was then turned smooth to eliminate uneven impact on the cutting tools when measuring tool wear rates.

Fig. 20. Gray iron brake drum castings. Left, casting after sample removal. Right, drum mounted on a CNC lathe for tool wear experiments.

The chemical composition of the two gray irons is presented in Table X. Casting “B” had significantly higher concentrations of Ti, Nb, and Sn than casting “A”. Other elemental concentrations were similar in both castings.

Table X. Chemical Compositions of Gray Iron Drum Castings (wt %)

Alloy	CIP-102-1-A	CIP-102-1-B
C	3.22	3.11
Si	1.76	1.85
Mn	0.60	0.71
P	0.025	0.024
S	0.070	0.075
Ni	0.054	0.048
Mo	0.008	0.008
Cr	0.239	0.203
Cu	0.51	0.63
Al	0.003	0.003
Ti	0.003	0.019
Sn	0.009	0.034
V	0.006	0.003
N	0.00655	0.00505
Zr	0.0045	0.0051
Nb	0.0074	0.013

Both tungsten carbide (WC) and silicon nitride (SiN) inserts were used in the machining experiments. Four surface speeds were used with the WC tools including 450 sf/min (140 m/min), 600 sf/min (180 m/min), 750 f/min (230 m/min), and 900 sf/min (275m/min). Speeds of 1800 sf/min (550 m/min), 2400 sf/min (730 m/min), and 3000 sf/min (915 m/min) were used with the SiN tools.

The machinability expressed as metal volume removed to an average flank tool wear of 6.5 mils (0.165 mm) is illustrated in Figure 21 as a function of turning speed. The volume of metal removed from Material A was higher using WC tools, at speeds below 900 f/min (275 m/min). The tool wear rates converged at 900 sf/min because of excessive heat at the WC tool tip.

Fig. 21 Gray iron brake drum machinability measured with two tool materials.

The machinability of Material “A” was better than Material “B” at all higher speeds used with the SiN tools. The volume of metal could be removed from “A” using SiN tools and was from about 35 to 25 in³ (575 to 410 cm³) at speeds of 1800 sf/min (550 m/min) to 3000 sf/min (915 m/min) before reaching the tool wear criteria of 0.065 inches (1.65 mm) average flank wear. The volume of metal could be removed from “B” material using SiN tools ranged from about 10 in³ (165 cm³) at 1800 sf/min (550 m/min) to about 5 in³ (82 cm³) at 3000 sf/min (915 m/min). Wear rates were linear with speed in all cases with R² statistic values ranging from about 0.96 to 0.98.

As previously observed, the volume of metal removed before reaching a specific flank wear criteria varied with tool material but material ranking in terms of machinability did not change with insert material. This indicates that the tool wear rate is being determined by metallurgical features of the castings.

The microstructures of both drums were examined using both optical and scanning electron microscopes (SEM). Ti-rich inclusions were found in both samples, and representative optical

and Energy Dispersive X-ray (EDXR) spectra from the Ti-rich inclusions are illustrated in Figure 22. The inclusion was located in the metal matrix and between the graphite flakes.

Fig. 22. Ti rich inclusions were observed in both drums. Left, a representative SEM image in CIP-102-1-B1 sample with the arrow pointing to a Ti-rich inclusion; right, EDS spectrum from the Ti-Rich Inclusion.

The number density of Ti-rich inclusions in the harder-to-machine castings was about 56 ± 4 inclusions per mm^2 compared to the “A” casting which contained about 9 ± 4 inclusions per mm^2 . Ti-rich inclusions, with their high hardness, increased the flank wear rate and, decreased tool life, and hence decreased machinability.

SUMMARY AND CONCLUSIONS

Procedures have been developed to accurately measure machinability of metals using drilling, milling, and turning operations. Machinability is measured in terms of either the volume of metal that can be removed before reaching a specified amount of tool flank wear or by measuring the rate of tool wear under specified machining conditions. These procedures allow tool wear measurements to be conducted, and the results correlated with microstructures and chemical compositions.

These procedures provide a means of quantitatively assessing the machinability of irons with reputed problems. Accurate data allows the most efficient way for improving machinability (without a sacrifice in properties) to be determined.

Tool wear rates have been found to be repeatable and consistent no matter what machining operation is used. The volume of metal removed may change from one machining operation or type of tool to another, but material rankings have not been found to change. An iron found to be hard to machine while being drilled is found to be harder to machine in turning operations. Similarly, irons that produce higher tool wear rates with WC inserts also produce higher wear rates when SiC or alumina tool materials are used.

This report illustrates the effects of variations in microstructure, strength, hardness, and trace elements on tool wear rates. Scores of irons have been examined and recorded. Only a few are presented in this report for illustrative purposes.

The major conclusions are as follows:

1. For best tool wear rates, irons should not have more pearlite than needed to produce the desired strength in the part. Irons with higher pearlite contents contain larger amounts of combined carbon, and the carbides increase tool wear rates.
2. Minor element concentrations, such as copper and tin, significantly affect tool wear rates. At the compositions evaluated in this study, both tin and copper made similar contributions to the increased tool wear rates (41% and 35% respectively).
3. The data suggests that at a given strength (pearlite content), tin might provide slightly lower tool rates than copper, but additional evaluations will be required to confirm this hypothesis.
4. Tool wear rates increase at a given strength as the number density and volume of dispersed micro-carbides and nitrides increase. The effects of zirconium in ductile iron and titanium and zirconium in gray iron have been documented. These materials can be picked up from charge materials and from some inoculants. Inoculants containing Ti and Zr can be beneficial under some circumstances, but excessive concentrations of these elements degrade machinability.

Correlations were developed between ultrasonic velocity, microstructure, certain mechanical properties, and tool wear rates, and the principal conclusions are listed below.

1. Ultrasonic velocity in gray iron decreases linearly with increasing graphite volume fraction. Higher ultrasonic velocities at a constant carbon equivalent indicate more microcarbides and higher tool wear rates.
2. At a constant carbon equivalent, an increase in Brinell hardness indicates more combined carbon, higher matrix strength, and higher tool wear rates. Pearlite was not found to have a statistically significant effect on ultrasonic velocity.
3. Ultrasonic velocity through ductile iron is affected by ferrite content, graphite volume fraction, and graphite roundness. Ultrasonic velocity decreased linearly with ferrite volume in ductile irons having less than 60% ferrite. A decrease in graphite roundness also decreased velocity. Higher graphite volume fractions decreased velocity, but there was considerable data scatter for reasons that have not been determined. Micro carbides did not have a significant effect on ultrasonic velocity within the range studied.
4. Ductile irons with higher volume fractions of pearlite or graphite had higher ultrasonic attenuation coefficients. Graphite particles produced a higher impedance mismatch with the metal matrix and caused ultrasound scattering.
5. Lower tool wear rates (better machinability) in gray iron were associated with lower ultrasonic velocities. Significantly higher amounts of metal could be removed from gray iron with a given tool when the first break ultrasonic velocity (FBUV) was less than 0.19 in. / μ s (4825 m/s).

6. Tool wear rates when machining ductile iron was better with higher graphite volume fractions, well-rounded nodules, and lower microcarbide contents. Microcarbides strengthen pearlite and increase the modulus by reducing the amount of free carbon.
7. Better ductile iron machinability was associated with lower ultrasonic velocities and microcarbide contents. Significantly greater amounts of metal could be removed from ductile iron castings whose ultrasonic velocity (FBUV) was less than 0.222 in. / μ s (5640 m/s). The correlation coefficients were low because other factors, probably strain hardening during plastic deformation, had a significant effect. The nondestructive techniques used to assess the microstructure did not account for the high strain to failure and work hardening during chip formation.

MILESTONE STATUS TABLE

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
1.1	Contact Foundries	11/99	12/99	Complete
1.2	Publish Project Description	11/99	01/00	Completed
1.3	Receive Problem Castings	03/2002	06/2003	Complete
1.4	Gather info on Problem Parts	06/2002	06/2003	Complete
1.5	Conduct Microstructural and Property Measurements	08/2002	08/2003	Complete
1.6	Provide Annual Reports or Yearly Progress Report on Results	10/2000	2001 2002 2003	Complete.
2.1	Develop Carbide/SN/CNB Matrices	02/2002	08/2003	Complete
2.2	Develop Procedure for Measuring Tool Wear	04/2000	04/2000	Complete
2.3	Conduct Machining Experiments on Gray Iron Submitted and Present Results	01/2002	06/2003	Complete
2.4	Conduct Machining Experiments on Ductile Iron Submitted and Present Results	03/2002	03/2002	Complete
3.1	Develop Standardized Procedure for Conducting Turning Experiments (Feeds and Speeds)	04/2000	Complete	Complete
3.2	Develop Standardized Methods for Tool Wear	07/2000	07/2000	Complete
3.3	Conduct Experiments on Gray Iron Submitted and Present Results	11/2002	08/2003	Complete
3.4	Conduct Experiments on Ductile Iron Submitted and Present Results	08/2002	08/2003	Complete
4.1	Spectral Acoustics	09/2001	09/2002	Complete
4.2	Torque-Thrust Measurements	09/2001	Not Used	Not an applicable technique. Work was suspended.

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
4.3	Difficult to Machine Casting Analysis	10/2002	08/2003	Complete
5.1	Steering Committee Select Grades of Iron to be Evaluated	05/2000	05/2000	Complete
5.2	Develop Cutting Plan for All Type of Specimens	05/2000	05/2000	Complete
5.3	Develop Specimen Geometries for Gray and Ductile Iron	09/2000	05/2000	Complete
5.4	Measure Properties on Irons Selected	01/2001	Suspended	Suspended with sponsor approval
5.5	Report Results	03/2001	Suspended	Suspended
6.1	Technology Transfer	05/2000	05/2000	
		09/2000	09/2000	
		01/2001	01/2001	
		05/2001	05/2001	
		09/2001	09/2001	
		01/2002	01/2002	
		05/2002	05/2002	
		01/2004	On Schedule	
6.2	Plant Trials with Improved Irons	09/2001	Complete	Complete
6.3	Summary Report	Dec 2001	Complete	2000, 2001, and
		Dec 2002	Complete	2002 reports
				Complete
6.4	Final Technical Report	Dec 2003	Complete	Complete

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