DOE/ID/13319--T1

CLEAN IRON PRODUCTION AND MACHINING TECHNOLOGY

YEAR 1 SUMMARY REPORT FOR THE PERIOD
JANUARY 1, 1995 - DECEMBER 31, 1995

From

UNIVERSITY OF ALABAMA AT BIRMINGHAM
Department of Materials and Mechanical Engineering
1016 15th Street South
Birmingham, Alabama 35294-4552

March 5, 1996

UAB THE UNIVERSITY OF
ALABAMA AT BIRMINGHAM

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

CLEAN IRON PRODUCTION AND MACHINING TECHNOLOGY

YEAR 1 SUMMARY REPORT FOR THE PERIOD
JANUARY 1, 1995 - DECEMBER 31, 1995

From

UNIVERSITY OF ALABAMA AT BIRMINGHAM
Department of Materials and Mechanical Engineering
1016 15th Street South
Birmingham, Alabama 35294-4552

March 5, 1996

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

CLEAN IRON PRODUCTION AND MACHINING TECHNOLOGY

Abstract

The first phase of this project was conducted to develop a technique for evaluating the machinability of gray and ductile iron. That technique was then used to measure the machinability of a variety of irons and determine the processing factors that influenced and controlled machinability. The procedure developed to evaluate machinability involved drilling holes with a feed rate of 0.009 in/rev at various surface speeds. High speed steel drills were used so wear was observed more quickly.

Microcarbides present in the irons were found to dominate the machinability. Pearlitic irons considered to have "acceptable" machinability (indicated either by tool life measured in the laboratory using high speed steel (HSS) drills or reports from commercial machine shops using other cutters) were found to contain from 8.9 to 10.5% by weight microscopic carbides.

The tool wear rate increased when machining at higher surface speeds or machining irons containing higher weight percentage of microcarbides. All irons containing above 11.5% microcarbides consistently exhibited poor machinability.

Tool wear results obtained using cubic boron nitride (CBN) cutters paralleled those obtained with HSS. Higher iron microcarbide concentrations produced faster tool wear.

Experiments are now being formulated to explore methods of improving iron machinability. Future work will extend the study to ductile irons.

INTRODUCTION

The Clean Iron Production and Machining project was undertaken in 1995 to develop benchmark data on the machinability of gray and ductile iron, compare benchmark data to results obtained on castings produced in commercial foundries, define inclusions and other conditions that degrade machinability, evaluate inoculants for their effectiveness in minimizing chill in thin sections, and demonstrate the best technology for mitigating factors that degrade machinability. This report summarizes the results obtained to date, focusing principally on gray iron.

The general approach to the project was to produce non-commercial castings in production foundries representing a wide variety of production practices. The castings produced included both plates and hollow cylinders with stepped cores. The plates were used to develop tool life evaluation procedures using high speed steel (HSS) drills. This procedure is being used to examine the effects of various plant processes and production variables on tool life. Little has been done with the hollow cylinders because these castings did not differentiate between the effects of casting processes on carbide formation in thin sections.

"Acceptable" and "hard-to-machine" castings were also solicited from sponsor companies to determine if differences could be found in the microstructures that would explain the differences in observed machinability. Samples of "acceptable" and "hard-to-machine" castings submitted by three companies have been analyzed.

Finally, an effort was begun to develop instrumentation that could be used to diagnose difficulties being experienced during machining that relate to machine tool operation. The instrumentation records acceleration-time response of transducers placed on both the castings being machined and on the machine tool being used.

RESULTS AND DISCUSSION

Seventeen batches of plate castings have been produced and eight batches evaluated using drill flank wear as the means of measuring the tool wear. The gray irons produced are summarized in Table I. The ductile irons produced (but not completely evaluated at this time) are summarized in Table II.

Laboratory Drill Wear Results on Plate Castings

The drill wear results obtained on gray iron are summarized in Figure 1 where tool life is plotted as a function of drill speed in surface feet per minute (SFM). Wide ranges in drill life are seen depending on the type and source of iron and the drill speed.

TABLE I.

GRAY IRON PLATE CASTINGS SUBMITTED FOR MACHINABILITY ANALYSIS

<u>Sponsor Code</u>	<u>Grade</u>	<u>Melting</u>	<u>Cooling Rate</u>
GS	40	Induction	Continuous Cast
G1	30	Cupola	Normal
G4	35	Cupola	Normal
G5	35	Cupola	Normal
G7	35	Cupola	Rapid
G7	35	Cupola	Normal
G7	35	Cupola	Slow
G7	35	Induction	Rapid
G7	35	Induction	Normal
G7	35	Induction	Slow
G8	40	Induction	Normal
G9	30	Cupola	Normal

TABLE II

DUCTILE IRON PLATE CASTINGS SUBMITTED FOR MACHINABILITY ANALYSIS

<u>Sponsor Code</u>	<u>Grade</u>	<u>Melting</u>	<u>Cooling Rate</u>
DS	65-45-12	Induction	Continuous Cast
D1	65-45-12	Induction	Normal
D1	80-55-06	Induction	Normal
D3	80-55-06	Induction	Normal
D4	80-52-03	Cupola	Normal

COMPARISON OF TOOL LIFE

Figure 1. Tool life Curves for HSS Drilling of Cast Iron Plates
(Number of Holes Drilled as a Function of Drill Speed).

Associated with each drill life curve is a foundry code, foundry melt practice, iron class, cooling condition, and two numbers such as 9.11/8.87. The first number in the pair indicates the weight percent of microcarbides in a pearlitic iron predicted by ThermoCalc(1), and the second number indicates the measured weight percent of microcarbides in the iron.

A predicted microcarbide weight percentage (MCWP) is calculated using a thermodynamic equilibrium based software package called ThermoCalc and the simple lever rule as applied to the iron-carbon phase diagram shown in Figure 2.(2) The solubility of carbon in austenite at the eutectoid temperature is determined using ThermoCalc. A specific chemistry is inserted into ThermoCalc such as 3.50% C and 2.25% Si. Then, using thermodynamic laws and equations, the phases and phase compositions present at specific temperatures are calculated. The carbon solubility in austenite can then be determined at the eutectoid temperature. The microcarbide weight percent can then be determined using the lever rule. The carbon solubility in austenite (determined from ThermoCalc), minus the carbon solubility in the ferrite is divided by the carbon solubility in the carbide minus the carbon solubility in the ferrite to calculate the microcarbide weight percent. This calculation is shown in Equation 1.

$$MCWP = \frac{X - 0.02}{6.67 - 0.02} \times 100 \quad [1]$$

For the composition given above, the carbon solubility in austenite is 0.651% which results in a microcarbide weight percent of 9.49%.

At a given drill speed, for example 130 SFM, approximately 20 holes were drilled before a specified flank wear occurred when drilling the Class 40 sand cast and continuously cast irons. These irons had microcarbide weight percents (MCWP) of 11.13 and 14.44, respectively. The number of holes increased to about 100 in the cupola-melted, Class 30 iron with a reduced MCWP value of 11.43, 300 in the induction-melted Class 35 iron with MCWP value of 10.68, 400 in the cupola-melted, Class 35 iron with a MCWP of 9.62, and 535 in the cupola-melted, Class 35 iron with a MCWP of 8.87. The tool life increased for a constant drill speed as the MCWP decreased.

Secondary effects, such as cooling rate on the run-out line are also evident in the data. For example, G75 was a cupola-melted iron that was poured on a DISA line and cooled on the line for about 18 minutes before shakeout. G76 was the same iron that was held an extra 17 minutes on the line before shakeout. About 30% more holes could be drilled in the castings cooled for a longer time in the mold compared to the normally cooled iron at a drill speed of 130 SFM. The slower cooling rate resulted in reduced MCWP from 9.62 to 8.87.

An even greater difference can be seen in drill life in the induction-melted irons poured on the same line. About twice as many holes could be drilled before tool failure in the slowly cooled, induction-melted iron (35 minutes run-out time) compared to the normally cooled iron (18 minutes run-out time). The microcarbide

Figure 2. The equilibrium Fe-Fe₃C and Fe-C(---) phase diagram. (2)

content was 10.68% in the slowly cooled, induction-melted iron and 10.98% in the normally cooled, induction-melted iron.

These results might suggest that cupola melting produces a more machinable iron. However, Curve 6 is the result obtained on a Class 30, cupola-melted iron and indicates lower machinability rating than the normally cooled Class 35, induction-melted iron. The iron has a higher microcarbide weight percent of 11.43.

The drill life results are replotted in Figure 3 as a function of weight percent microcarbide for the various irons. The three curves represent drill life at tool speeds of 120, 130, and 140 surface feet per minute. Drill life progressively decreased as microcarbide content increased. Above 11.5% by weight microcarbide, the drills exhibited a low life even at the lowest test speed. Additionally, as surface speed increased, tool life decreased.

A high correlation ($R^2 > .95$) has also been found between nitrogen concentration and tool life. Nitrogen may have a stabilizing effect on the microcarbides and, thus, be contributing to tool wear.

Analysis of Commercial Castings

The relationships observed in the tool wear results obtained in the laboratory appear consistent with the results obtained in three sets of "acceptable" and "hard-to-machine" commercial castings submitted by sponsor companies. For each pair of "acceptable" and "hard-to-machine" castings, the microcarbide weight percent was greater in the "hard-to-machine" castings. In these cases, the castings were reported to be "hard-to-machine" by commercial machine shops, but the degree was subjective.

The results of the microcarbide analysis are presented in Tables III-V for disc hubs, cylinder bores in diesel blocks, and diesel heads, respectively. In each case, Thermocalc was used to predict the equilibrium microcarbide percent assuming a fully pearlitic microstructure. This calculation was made based on the nominal carbon and silicon concentration, and the predictions may change when a complete trace element analysis is obtained. The predicted microcarbide content is followed by an experimentally determined microcarbide content.

Thermocalc predicted an equilibrium carbide weight percent of about 9.49 in the hub irons, as presented in Table III. The weight percent of microcarbides in the irons considered to have acceptable machinability ranged from 9.47 to 10.53. The weight percent of microcarbides in the irons considered to have poor machinability ranged from 13.23 to 13.68.

Similar data on several diesel blocks being machined with CBN inserts and one cylinder head are presented in Table IV. The first iron composition was for a Foundry B cylinder bore having a nominal carbon of 3.25% and silicon of 2.30%. These cylinder blocks had an "acceptable" machinability. The predicted microcarbide content was 9.47%, and the measured microcarbide content was 9.92%.

Figure 3. Effect of Microcarbide Content in Gray Iron on Tool Life (All Gray Irons).

TABLE III

CORRELATION BETWEEN SUBJECTIVE MACHINABILITY RATINGS ON DISC BRAKE HUBS
AND EXPERIMENTALLY DETERMINED MICROCARBIDE CONTENTS IN THE CASTINGS

UAB SAMPLE NUMBER	DESCRIPTORS	NOMINAL COMPOSITION		PREDICTED MICRO- CARBIDE WT (%)	EXPERIMENTAL MICRO CARBIDE WT (%)
		C (%)	Si (%)		
CIP-22-2G	"Acceptable" Machinability Heat Date 1425 Bored Surface	3.50	2.25	9.49	9.47
CIP-22-2G	"Acceptable" Machinability Heat Date 1425 Faced Surface	3.50	2.25	9.49	10.53
CIP-22-1P	"Hard-to-Machine" Heat Date 3205 Bored Surface	3.50	2.25	9.49	13.23
CIP-22-1P	"Hard-to-Machine" Heat Date 3205 Faced Surface	3.50	2.25	9.49	13.68

TABLE IV

CORRELATION BETWEEN SUBJECTIVE MACHINABILITY RATINGS FROM CBN TOOLS USED ON BORED
CYLINDER BLOCKS AND EXPERIMENTALLY DETERMINED
MICROCARBIDE CONTENTS IN THE CASTINGS

(Blocks were machined using CBN inserts)

UAB SAMPLE NUMBER	DESCRIPTORS	NOMINAL COMPOSITION C (%) Si (%)	PREDICTED MICRO- CARBIDE WT (%)	EXPERIMENTAL MICROCARBIDE WT (%)
CIP-13-TSR3	Foundry B Cylinder Bore #403, Semi-Rough Finish, "Acceptable" Machinability	3.25 2.30	9.47	9.92
CIP-18-NTC1	Foundry A Cylinder Bore #403 with Foundry B Chemistry "Acceptable" Machinability	3.65 2.24	9.49	9.62
CIP-13-NSR3	Foundry A Cylinder Bore #403 with August Chemistry, Semi-Rough Finish, "Marginal" Machinability	3.48 2.00	9.55	11.13
CIP-18-NFC2	Foundry A Cylinder Bore with February Chemistry, "Poor" Machinability	3.47 2.00	9.55	10.98
CIP-23	Foundry A Heads, "Broke Drills Left & Right"			12.6

The second iron composition was from a Foundry A cylinder bore made with a Foundry B chemistry having a nominal carbon of 3.65% and silicon of 2.24%. Cylinder blocks with this iron composition had "acceptable" machinability. The predicted carbide weight percent was 9.49, and the actual microcarbide weight percent was 9.62.

The third and fourth irons were poured at Foundry A and made with "normal" chemistry in August and February 1995, respectively. These irons had a nominal carbon of 3.48% and silicon of 2.00%. Cylinder blocks with this chemistry had "marginal" to "poor" machinability rating. The predicted microcarbide weight percent was 9.55, but the actual microcarbide weight percent ranged from 10.98 to 11.13.

The last entry in Table IV is for a diesel head produced at Foundry A that "broke drills left and right" at the machine shop. Neither nominal chemistries nor predicted microcarbide contents are available, but this iron had the highest microcarbide content of any of these irons at 12.6%.

The results obtained on several cylinder heads from another foundry are presented in Table V. These castings were made using both no-bake and green sand casting processes to produce the same head in all cases. Two casting regions were examined. The "thin" section was about 1" thick and the "thick" section was about 4" thick.

Thermocalc predicted an equilibrium microcarbide weight percent of about 9.53 in the green sand castings having acceptable machinability and 9.53 in the no-bake castings having acceptable machinability. The weight percent of microcarbides in the thin sections considered to have acceptable machinability ranged from 9.47 to 9.62. The weight percent of microcarbides in the thin sections in the no-bake castings considered to have poor machinability was in the range of 10.23 to 11.13.

The weight percent of microcarbides found in the thick sections in castings considered to have acceptable machinability ranged from 9.77 to 11.13. The weight percent of microcarbides found in the thick sections in castings considered to be "hard-to-machine" machinability ranged from 12.03 to 12.63.

While the "equilibrium" microcarbide values may change when a more complete chemical analysis is obtained, there is no doubt that the poorly machinable irons contained a higher concentration of microcarbides than the companion irons with acceptable machinability.

There are three factors that probably control the formation of carbides in iron. Those are:

- (1) the cooling rate of the iron from the eutectic temperature to the eutectoid temperature,
- (2) the concentrations of pearlite stabilizing elements (Cr, Mn, Mo, N, etc), and

TABLE V
CORRELATION BETWEEN SUBJECTIVE MACHINABILITY RATINGS OBSERVED DURING DRILLING OF CLASS 40 GRAY
IRON HEADS AND EXPERIMENTALLY DETERMINED MICROCARBIDES IN THE CASTINGS

UAB SAMPLE NUMBER	DESCRIPTORS	NOMINAL COMPOSITION C (%) Si (%)	PREDICTED MICRO- CARBIDE WT (%)	EXPERIMENTAL MICROCARBIDE WT (%)
G8H-2-B	"Acceptable" Machinability Green Sand Mold "Thin" Section	3.28 2.08	9.53	9.62
G8H-5-B	"Acceptable" Machinability Green Sand Mold "Thin" Section	3.24 2.15	9.52	9.47
G8E-8-B	"Hard-to-Machine" January No-Bake "Thin" Section	3.24 2.03	9.54	10.23
G8E-9-B	"Hard-to-Machine" January No-Bake "Thin" Section	3.23 2.06	9.53	11.13
G8H-5-203	"Acceptable" Machinability Green Sand Mold "Thick" Section	3.24 2.15	9.52	9.77
G8H-5-205	"Acceptable" Machinability Green Sand Mold "Thick" Section	3.24 2.15	9.52	11.13
G8E-9-203	"Hard-to-Machine" January No-Bake "Thick" Section	3.23 2.06	9.53	12.03
G8E-9-205	Hard-to-Machine January No-Bake "Thick" Section	3.23 2.06	9.53	12.63

- (3) the concentrations of elements that retard diffusion of carbon from austenite to graphite including tin, antimony, and copper.

The practical question is going to be how best to control and reduce the microcarbides under specific situations.

Machine Tool Dynamics

It is recognized that machine tool dynamics can radically affect tool life. However, just how to analyze tool dynamics is not established, and a systematic procedure is now being developed. An initial analysis of one "troubled" machining center using CBN inserts to machine a Class 35 gray iron was conducted and subsequent corrective procedures applied. Increasing the tool clamping force (to achieve more rigidity) and altering the depth of cut increased the tool life from 400 parts machined per set of inserts to 4000 parts. Tool operating parameters were adjusted so there was no sacrifice in productivity while the tool life was increased by a factor of 10. This procedure must be tested in other shops and the results correlated.

FUTURE RESEARCH

Future research will shift to ductile iron and to examining processing factors that might be changed to improve machinability. Improved machinability might be achieved with special inoculants, trace element concentration control, cooling rate control, and perhaps others. Experiments to determine the influence of inoculants on microcarbide volume are now being planned.

ACKNOWLEDGEMENT

We wish to express grateful acknowledgement and deep appreciation to the many companies and individuals who participated in the project by providing advice, descriptions of particular difficulties, defects, and guidance regarding the most fruitful areas for investigation. In addition, we would like to express our appreciation to the sponsoring companies that interrupted hectic production schedules to produce experimental test castings.

A special word of thanks goes to Dr. Joe Santner at the American Foundrymen's Society for guidance and insight throughout the project. Mr. Daniel Twarog, currently the Executive Vice President of North American Die Casting Association, also provided significant assistance.

We also wish to express our appreciation to the Department of Energy for technical assistance and partial funding of the project. Special thanks go to Mr. Bob Trimberger and Dr. Manohar Sohal. Matching funds were provided under contract DE-FC07-94ID13319 with Amendments.

Our hope is that the information contained in this report will be of assistance to companies throughout the United States in advancing the technology of Clean Iron Production and Machinability.

Submitted by,

Jeff Sprague
Masters Degree Candidate

Submitted by,

Carl DelSorbo
Masters Degree Candidate

Zoe B. Dwyer, Ph.D.
Research Engineer

Robin Griffin, Ph.D.
Electron Optic Laboratory
Manager

Evangelos C. Eleftheriou, Ph.D.
Assistant Professor

Harry Littleton
Engineering Manager

Approved by:

Charles E. Bates, Ph.D.
Research Professor

(CLI95SUM.ECA)

REFERENCES

1. Thermocalc, Division of Computational Thermodynamics, Department of Materials Science & Engineering, Royal Institute of Technology, S100-44, Stockholm, Sweden.
2. Baker, H., ed., et al. ASM Handbook: Alloy Phase Diagrams, Volume 3. Materials Park, Ohio: ASM International, 1992.

USE OF THIS REPORT AND INFORMATION
CONTAINED THEREIN

Publicity

This report and the information contained therein is the property of the individual or organization named on the face hereof and may be freely distributed in its present form. However, the University of Alabama at Birmingham (UAB) hereby reminds Sponsor that no advertising or publicity matter, having or containing any reference to the University of Alabama at Birmingham, shall be made use of by anyone, unless and until such matter shall have first been submitted to and received the approval in writing of UAB. (UAB does not usually approve any type of endorsement advertising.)

Limitation of Liability

The faculty and staff of UAB associated with this project have used their professional experience and best professional efforts in performing this work. However, UAB does not represent, warrant or guarantee that its research results, or product produced therefrom, are merchantable or satisfactory for any particular purpose, and there are no warranties, express or implied, to such effect. Acceptance, reliance on, or use of such results shall be at the sole risk of Sponsor. In connection with this work, UAB shall in no event be responsible or liable in contract or in tort for any special, indirect, incidental or consequential damages, such as, but not limited to, loss of product, profits or revenues, damage or loss from operation or nonoperation of plant, or claims of customers of Sponsor.

Report No.: CIP Sponsor Summary - Year 1

To: Clean Iron Sponsor Companies

Date: March 8, 1996

UAB Account No. 527965, 633157

E-File: cli95sum.eca

\BOILER\LMTLIAB\RPTLANG.All