1986

Inferential Operations Research on Surface Finish of Castings

D. C. Ekey
University of Richmond

SILVER ANNIVERSARY PAPER

Inferential Operations Research on Surface Finish of Castings

D. C. Ekey
University of Richmond
Richmond, Virginia

ABSTRACT

This paper reports the result of an experiment using statistical research methodology to evaluate previous findings, identify new effects and focus on potential future research efforts to improve the control of casting surface roughness.

The objective of developing a functional equation to predict casting surface roughness was achieved. A reliable and valid methodology for obtaining operational "surface imprints" of casting surface roughness was developed.

Gray iron castings within a weight range of 1 to 7000 pounds were studied. The population of 142 surface roughness measurements came from five foundries in the northeast regions of Pennsylvania, Vermont, Maine, and Massachusetts. The dependent roughness variable had an average surface roughness of 444 microinches arithmetical average (AA) with a standard deviation of 254 microinches.

Main effect variables of sand fineness and mold wash were found to have significance. The nonlinear importance of sand fineness and the interaction of metal pressure and sand fineness were clarified.

Questions were raised on the absence of significance of effects of mold hardness and casting weight on surface finish. The feasibility of applied research in the foundry operating environment was determined to be a practical research environmental option.

INTRODUCTION

Casting finish is becoming of increasing importance to foundrymen, their competitors and consumers. Quality is a major focal point of current international manufacturing competition and related U. S. balance of trade.

The importance of casting surface finish is based on several relevant factors. Major factors are appearance, economy of allied vertical processing, reliability, functional design requirements and economics.

Casting surface finish varies over a broad range of measurement. Die castings can be produced with roughness values as low as 20 microinches, investment castings can achieve, at least, a 60 microinch finish. Permanent mold magnesium alloy castings have an average surface finish of 150 microinches, according to studies by Gantz.[15] This research included, in part, green sand production (no mold wash) of 40-lb gray iron castings that yielded surface finish values in the range of 150-200 microinches. At the extreme end of surface finish there were gray iron castings with an average roughness of over 1000 microinches AA.

The significance of previous research activities and the importance of the research goals resulted in an in-depth literature study.

The technology to produce routinely excellent casting surface finishes exists. How else can one explain the observed routine production of 3.5-ton gray iron castings with surface roughness values of 300 microinches AA?

Previous Research

Major research efforts on casting surface finish started after World War II, were prolific in the fifties, dropped to a minimal level in the sixties, and in the seventies produced a record level of significant worldwide research activity on casting surface finish and casting tolerances. In recent years Russian and European scientists have been active in casting surface finish research.

A chronological list of research activities and findings from the early thirties to the present bears a fundamental logical continuity of theoretical concepts and continuity of research efforts.

The early (1953) contribution of Fairfield and McConachie[14] related the effect of sand flowability on casting surface finish. In their study, they used a nonstandard index measure of casting finish, the loss in weight by buffing the test casting to a smooth finish. They found that pouring temperature, moisture, sand preparation and ramming affected surface finish.

These findings were in agreement with the earlier work (1951) of Gonya and Ekey[16] which determined that percent moisture in the sand mix, sand grain distribution, static metal pressure head and ramming affected both surface finish and metal penetration in brass castings. This research was based on the first application of statistical mathematics in design of foundry research experiments.

In 1954, Ekey and Goldress[13] presented research with the use of root-mean-square (RMS) measurements of gray iron casting surface finish. Their work also used a statistical mathematical design to determine the effects of sand fineness, metal pressure and wood flour sand additive on casting surface finish. In this study sand fineness and metal pressure, but not wood flour additives, were found to affect significantly gray iron casting finish.

The need to establish standards for as-cast surfaces was recognized by Loder[12] in his 1954 research. Various grades of sandpaper were considered as a medium of surface finish comparisons. The lack of durability of the sandpaper surface motivated him to cast eight sandpaper surfaces in various grades on aluminum blocks. These casting finish standards served as permanent visual surface standards of comparison with casting surfaces.

Research on core sand and green sand mixtures (1954) by Parker[11] resulted in the conclusion that gray iron castings produced by conventional methods could give a very smooth surface finish and a very close dimensional tolerance. He suggested that finer sands enhance casting surface finish.

A study of various alloys in shell molding (1955) by Flinn, Smith, Pierce and Youngdahl[10] determined that lighter casting sections of SAE 4140 steel and gray iron shell molded castings had better surface finish than heavy sections. This result was attributed to surface reaction in the mold. They also noted that varying the resin content of the shell-sand mix between 4 and 12% had little effect on surface quality. A strong recommendation based on this research was to investigate further the effect of mold washes on surface quality.

The first evidence of interaction among significant variables affecting the surface finish of gray iron castings resulted in a study by Yard and Ekey in 1956.[9] This research design was based on a mathematical-statistical model for analysis of variance (ANOVA). The multivariate experimental design proved the existence of interaction between the main effects of sand fineness and metal pressure. A fourfold increase in metal pressure resulted in a tenfold increase in gray iron casting surface roughness for very coarse sand mixes.

The use of anionic surface agents in sand mixes as a wetting agent was investigated by Vingas and Lewis (1956).[8] It was found that a surface-active agent of sulfonated aliphatic polyester produced a casting surface finish superior to traditional green sand mixes.

Research on the influence of the elements of boron, titanium and silicon on surface defects was published by Powell and Taylor.[7] This work, in 1958, showed that 0.030% boron was sufficient to produce steel casting surfaces comparable to the excellent surface obtained with cast iron. Their work strongly supported the time-relationship theory of surface defects.

Parr[6] determined, in 1973, that a chromite-zircon mixture resulted in a superior casting surface finish in the production of 200-lb railway castings. He reported that an adverse surface finish was obtained with the use of chromite sand without zircon in the mix.

Four Russian researchers, Sigarev, Poludenov, Kurochin and Kansterov,[5] reported in 1974 that silicate-bonded sand shell molds produced on jolt molding machines produced castings with superior surface finish and dimensional accuracy. The CO_2 gassed shell molds were compared to green sand molds.

The influence of mold-gas pressure in casting surface finish was reported by a Russian, Gaisin[4] (1975). This research concludes that damage to the surface layers of sand under gas pressure set up during pouring is one of the significant factors that determines the surface finish of castings. Adequate venting and reduced gas pressures were shown to improve the surface finish of steel body castings.

Russian research on metal stream oscillations during pouring, in 1976, is highly theoretical. This work by Ryzhkov and Gini[3] claims that dampening effects of proper venting during vacuum suction pouring affects surface finish. They report that the surface finish of impeller castings, cast with controlled metal turbulence, was equal to die castings.

German researchers, Seifert and Fischer,[2] have investigated the surface finish of continuous casting of tin and lead in molds excited by ultrasonic waves. Precise surface finish measurements showed the relationship between ultrasonic treatment and surface finish. Exposure of the mold to ultrasonic waves resulted in significant improvement of cast-surface finish. The authors conclude that a reduction in temperature fluctuation at the metal-mold interface, due to ultrasonic treatment, gives rise to improved surface finish.

Recent research from Great Britain by Bragg[1] (1978) investigated the effect of increasing metal head pressure on surface finish of castings. The experimental results showed that surface finish of cast iron deteriorated with increasing head pressure, which varied from 0.143 to 1.400 meters. Bragg also studied resin-bonded sand, CO_2-silicate sand and green sand. The CO_2-silicate sands had the superior finish, and the resin-bonded sand yielded a surface finish better than green sand.

RESEARCH OBJECTIVES

Research literature of the past fifty years identifies numerous operating variables that affect casting surface finish. This literature also highlights areas for additional research. The demonstrated significance of surface finish to the foundry industry was influential in the development of the several research objectives in this paper.

A major objective was to bridge the potential credibility gap between laboratory research and foundry operations. Traditional research methodology focuses on scientific investigation in a controlled environment providing minimum error in the evaluation of possible relationships between a dependent variable and a variety of suspect independent variables. Practitioners occasionally question the utility of some conclusions reached in the sheltered "ivory towers."

Numerous research projects are more efficiently pursued in the real-world operating environment. The operating environment can introduce large research errors which challenge the researcher's creativity. This parameter of experimental error delayed many research activities outside of the laboratory until agricultural scientists successfully demonstrated that statistical mathematics could identify, measure and help control the experimental error which clouded decisions on the significance of cause and effect relationships found in the field.

Numerous disciplines including ergonomics, political science, social science, medicine, psychology, manufacturing, economics, business and finance have sustained research efforts in the real-world environment using established applied methodology.

A basic hypothesis was that the existing laboratory results could be verified and evaluated in foundry production operations research. It was also hoped that the production operations environment could be demonstrated as a meaningful research laboratory.

Other research objectives were: to develop a reliable and valid casting surface imprint methodology; to establish operating thresholds and parameters for casting surface finish in typical gray iron foundry production operations; to evaluate the effect of variables such as mold wash (a suggestion of Flinn[10]); to evaluate molding materials such as CO_2-silicate, shell and green sand;[1,5] to evaluate cope and drag variations in surface finish; to evaluate "pressure" versus "swing" mold-pattern interfaces of horizontal molding machines; to evaluate core versus mold casting surface-interfaces; and, hopefully, to identify future research opportunities.

The breadth of this research would be impossible with the given resource constraints of time and money which permeate all research activity. The mathematical calculations in this research would require about ten man-years of work. A modern electronic digital computer calculating at a feasible rate of 2 million multiplications a second performed all the required

Table 1. Independent Variables Investigated

NO.	IND. VAR. CODE	DESCRIPTION OF INDEPENDENT VAR.	NUMERIC RANGE OF VAR.
1.	AFS	Sand Grain-Fineness	35-95
2.	POURT	Metal Pouring Temp.	1327C(2420F)-1488C(2710F)
3.	COPEDG	Cope vs. Drag Casting Surface*	1(Cope), 2(Drag)
4.	SIDE	Pressure vs. Swing Side of Casting Surface*	1(Pressure), 2(Swing)
5.	CO	A Participating Gray Iron Foundry*	0,1,2,5,7
6.	WT	Casting Weight in lbs.	3-7000
7.	SURF	Mold vs. Core Casting Interface*	0(Mold), 1(Core)
8.	MATL	Primary Molding Material*	0-4
9.	HARD	Green-Hardness Test (Dietert)	65-100
10.	SMOLD	Sand Molding-Compaction Process (hand, machine, slinger)*	0,2,3
11.	WASH	Refractory Coating of Mold/Core Surface*	0(Yes), 1(No)
12.	POURHT	Hydraulic Pressure Head in Inches from Pouring Cup to Test Surface of Casting	4-66
13.	HYDPS	Density Multiplied by POURHT (lb./sq.in.)= (0.2564 lb./cu.in.)(in.)	1.026-16.92
14.	AXHT	(AFS)x(POURHT)	140-6270
15.	TXHT	(POURT)x(POURHT)	9,680-178,860
16.	HRDSQ	$(HARD)^2$	4,225-10,000
17.	WXM	(WASH)x(SMOLD)	0,2,3
18.	COSQ	$(CO)^2$	0-49
19.	COXWASH	(CO)x(WASH)	0-7
20.	HARDP	$(HARD)^{1.3}$	102-398
21.	AFSXHD	(AFS)x(HARD)	2275-9500
22.	HYDPSP	$(HYDPS)^{1.5}$	1.04-69.6
23.	HTSQ	$(POURHT)^2$	16-4356
24.	COXSM	(CO)x(SMOLD)	0-21

* Nominal or Dummy Variables

calculations in less than one or two hours. This modern technological computing resource, when coupled with modern statistical theory, provides experimental design opportunities which were unheard-of twenty-five years ago.

DESIGN OF THE EXPERIMENT

The experimental environment was selected on a pragmatic basis. Five typical gray iron foundries were selected using a random opportunity criterion, subject to implied experimental design restraints. Foundry operations were selected to represent a broad geographical region including Pennsylvania, Vermont, Massachusetts and Maine. The gray iron cast products were in a weight range from 1 to 7000 pounds, and included both electric arc and cupola melting.

The twenty-four independent variables investigated and their range of variation are listed in Table 1. The effect of these independent variables on the dependent variable of casting surface finish measured in microinches AA was investigated.

One hundred and forty-two samples of surface finish were obtained. Sample stratification by casting weight, molding process, molding material, pouring height, pouring temperature and mold wash influenced the randomly-selected casting surfaces, subject to "nesting" within each foundry. One foundry, using a contemporary horizontal molding machine, was selected on a preferential basis.

The basic experimental design was predicated on the use of experimental statistical methods. Multiple regression and correlation, F-tests, t-tests and analysis of variance (ANOVA) were used to evaluate the nature and significance of effects of the 24 independent variables on the dependent variable of surface finish.

Casting finish varied from a smoothness value of 120 to a high roughness of 1400 microinches AA. The total population of castings had a mean surface finish of 444 microinches AA with a standard deviation of 254.

The experimental results supported previous research findings, proved the wisdom of suggestions by early investigators, added refined interpretation of existing research conclusions and established new significant relationships among the variables studied.

A major obstacle to the implementation of the research goals was obtaining accurate data on surface measurements of castings produced in the foundry environment. Logistic, technological and economic barriers had to be resolved. The need to obtain surface measurements of heavy castings at operations remote from the immobile complex-sensitive surface measurement equipment indicated the need for a reliable and valid method to provide a sturdy impression-record of casting surface roughness. This problem created a miniresearch project to develop an economical, transportable, permanent "surface imprint" compatible with the required surface measurements in microinches.

IMPRESSIONS OF CAST SURFACES

The operational characteristics of instruments used to provide reliable and valid measurement of surface finishes in micro inches of measure restricts the size, weight and shape of cast surfaces subject to measurement. The system used in the research has four major components; viz. the control, direct-coupled probe, drive and dual-channel recording units. To minimize vibratory distortion in measurements, these units are mounted on a 3000-pound marble slab which is supported by air bags, Fig. 1.

An economical, valid and reliable method was developed to

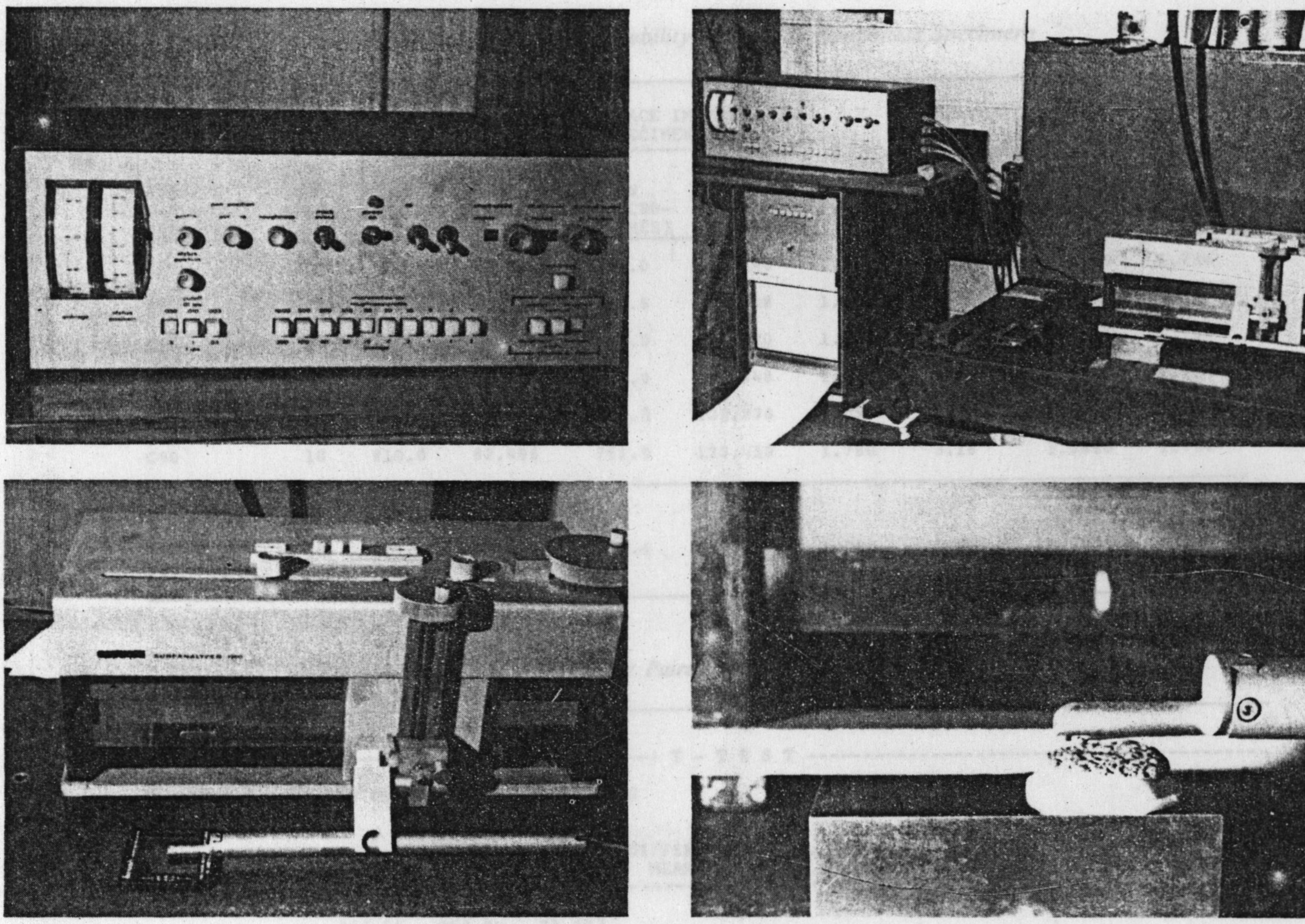

Fig. 1. Surface roughness measurement equipment.

obtain "surface imprints" of as-cast surface finishes in the operating environment. The cast surface finish specimens provide a permanent replication of the cast finish and a source of surface measurement data in the laboratory.

An epoxy resin (polymeric) material was impressed in the test area of casting surface finish and a negative impression obtained. Finger pressure is adequate to obtain an excellent impression. A silicon parting agent was used. The epoxy material was secured in a plastic "cap" holder prior to impressing on the casting surface. The cap became a permanent container for curing, transportation, storage and surface measurement analysis of the roughness imprint. The epoxy material cures to a hardness which readily accommodates the operation(s) of the needle-point stylus used in surface finish measurements. The stylus had a 0.0001-in. radius point and a stylus pressure of 200 milligrams. The stylus traverse excursion of the test surface was approximately 0.250 inches.

Reliability and Validity of Surface Imprints

The reliability and validity of the imprint reproduction of casting surface finishes was critical to the feasibility and quality of this research. The moving average roughness measurement in microinches AA provided a sensitive threshold. This sensitivity highlighted both assignable and error sources of surface roughness.

Since great error measurement opportunity permeates this kind of research, it was necessary to develop the surface imprint method. A subexperiment was made of this allied research project in development of a methodology to improve both the efficiency and broaden the opportunity for measurements of cast surfaces.

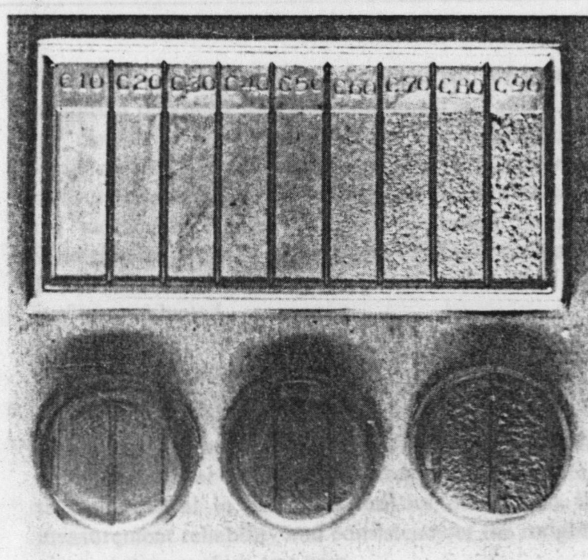

Fig. 2. Casting surface gauge and impression specimens.

Table 2. Validity and Reliability of Surface Roughness Specimens

		STANDARD SURFACE (AA)		SURFACE IMPRESSION SPECIMEN (AA)					
SURFACE SAMPLE REFERENCE	EACH SAMPLE SIZE n	MEAN (MICRO-INCHES)	STANDARD DEVIATION (MICRO-INCHES)	MEAN (MICRO-INCHES)	STANDARD DEVIATION (MICRO-INCHES)	OBSERVED F-Value	CRITICAL F-Value 1% LEVEL	OBSERVED t-Value	CRITICAL t-Value 1% LEVEL
C10	10	71.5	9.144	74.0	6.146	2.125	3.18	0.7575	1.734
C20	10	126.0	7.746	121.5	6.258	1.531	3.18	1.5063	1.734
C40	10	258.5	16.841	250.0	14.720	1.309	3.18	1.2667	1.734
C70	10	547.0	89.200	556.0	86.948	1.052	3.18	0.2408	1.734
C80	10	701.0	98.257	676.0	102.870	1.096	3.18	0.5858	1.734
C90	10	810.0	92.496	761.0	123.419	1.780	3.18	1.0590	1.734
ENTIRE GROUP(S)	60	412.83	286.107	399.6	275.312	1.080	1.90	0.2606	2.617

Table 3. T-Tests for Paired Observations in Sampling

T - T E S T

T - TEST FOR PAIRED OBSERVATIONS IN SAMPLING

VARIABLE	N	MEAN	STD. DEV.	STD. ERROR	(DIFFERENCE) MEAN	STD. DEV.	STD. ERROR	CORR.	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.
RMS	122	369.50	223.84	20.26	-2.95	238.46	21.59	0.43	0.00	-0.14	121	0.89
RMS2		372.45	224.49	20.32								

Random surface imprint specimens were made of six test surfaces on the Cast Surface Comparator, a standard cast surface test gauge, Fig. 2. Surface measurements at random locations were made of both conditions; six standard test surfaces and the comparable six standard imprint specimens. The data from these 120 surface measurements were used in statistical t-test and F-test analyses to evaluate the reliability and validity of the "surface imprint" measurement methodology.

A t-test[20] was used for inferences about the differences between the means of surface roughness measurements for the two surfaces, i. e., the "standard surface" and the "surface impression specimen." This test of validity at the one per cent level of confidence, Table 2, indicated that there was no significant difference in the average microinch roughness measurement AA obtained from the matched samples. Validity of the test was proved.

The F-test[21] was used for inferences about the differences in variances between the roughness measurements from the "standard surfaces" and the "surface impression specimens." A condition of *homoscedasticity*, equal variances, is required to verify reliability of the roughness measurements obtained from the "surface impression specimen."

To test the equality of the several variance estimates of the population of possible surface measurements, two sources of sample variances for each of the six standard surfaces provided computed variance estimates for each pair of samples which permitted reliability inferences presented in Table 1. At the one per cent level of significance, the null hypothesis that the variances of the data from samples of "standard surface" measurements equaled the variances of the data from samples of the "surface impression specimen" was tested. Data in Table 2 show that the ratios of the sources of variance estimates have an F-test value less than the critical F-value for all of the six test surfaces evaluated.

t-Test for Paired Observations

To check both the reliabiity of the surface imprint measurements and possible error in sampling, a pair of samples were obtained for each test condition. These pairs were assumed to be identical in all characteristics other than factors of measurement reliability and consistency of the roughness for a given casting surface test area.

The t-test for paired observations in sampling shows that there is no significant difference in paired roughness measurements at the 11% level of confidence. This result indicates that a minimum of error was produced by the sampling-measurement procedures used in the experiment, Table 3.

It was concluded that the "surface impression" methodology developed in this research for surface finish analysis was both

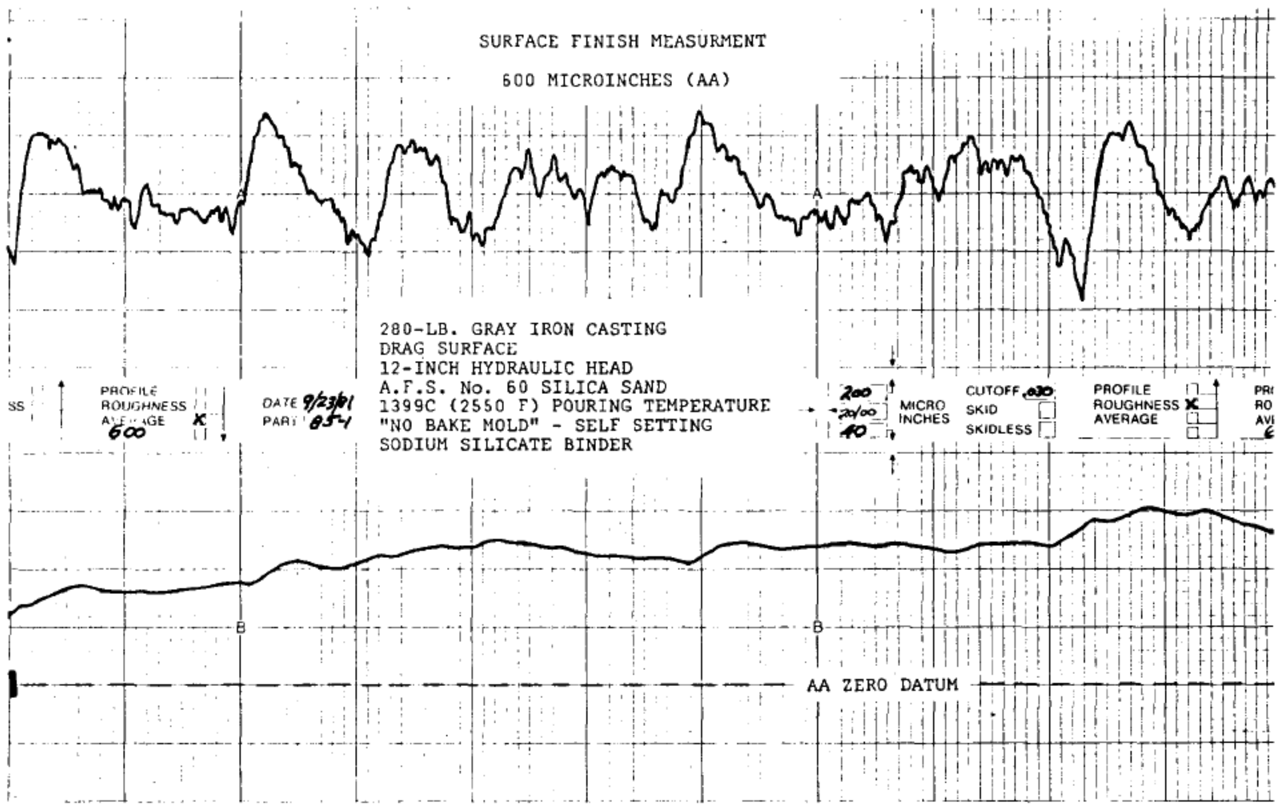

Fig. 3. Graph-plot of typical surface roughness measurement.

valid and reliable. Therefore, the allied research results should have a minimum error from surface measurement operations.

Surface Roughness Tests

Standards of measurement and description of surface finish are described by Loder[12] as one of the major elements of error encountered by the foundryman in production of castings and judgments on the quality of casting.

Surface measurement techniques encompass a broad spectrum. The analytical process ranges from visual and feeler comparators, microprocessor stylus recordings in microinches, optical comparators and interferometry, to laser systems.

Various standards for specification and measurements of cast surfaces have existed for many years. However, the concepts are not understood or used well, and statements about surface roughness are used loosely.

Terminology of the American National Standards Institute emphasizes three characteristics: roughness, waviness and lay. The numerical measurement of surface roughness is expressed in microinches and represents the average deviation from a central place to the surface peaks and valleys. This average of peaks and valleys from the central place was originally expressed as the root-mean-square (RMS). In 1955 the RMS was placed by the arithmetic average AA. An approximate conversion to RMS from AA is given by a multiplier factor of 1.11.

Surface roughness measurements in this research were calculated with microprocessor computer analysis which provided both a moving average AA and roughness profile outputs, Fig. 3. A standard roughness-width cutoff of 0.030 in. was used throughout the surface measurement tests, and the stylus excursion distance was a minimum of 1/4-inch. All surface test conditions were subjected to pre- and post-calibration tests of instruments, Fig. 4. The cast surfaces were not evaluated for the characteristics of lay and waviness. Lay is not a characteristic condition of cast surfaces and waviness was not pertinent to this investigation.

ANALYSIS OF DATA

The statistical experimental designs used permit the study of different variables in multiple-simultaneous analysis and also the opportunity to focus on individual variables which prove or appear to be significant. An additional capability is to develop functional relationship(s) between one or more independent variables and the dependent surface finish variable.

All 24 independent variables studied, Table 1, were used in a multiple regression model to estimate the values of the dependent variable of surface finish. There are three general purposes of multiple regression and correlation analysis:

1) to establish an equation to estimate the surface roughness from values of two or more independent variables;
2) to provide measures of the error of estimation; and,
3) to determine the proportion of observed variance in surface finish explained by the independent variables.

In the selection of independent variables studied for inclusion or deletion from the regression equation, a "step-wise forward inclusion" was used subject to an F-test level of confidence of one per cent for the particular candidate variable. In addition, the researcher used experiential-judgment to delete, but not add, variables considered inappropriate for the research goals. This initial statistical analysis identified nine variables, three of which were interactive, that affected casting surface finish, Table 4.

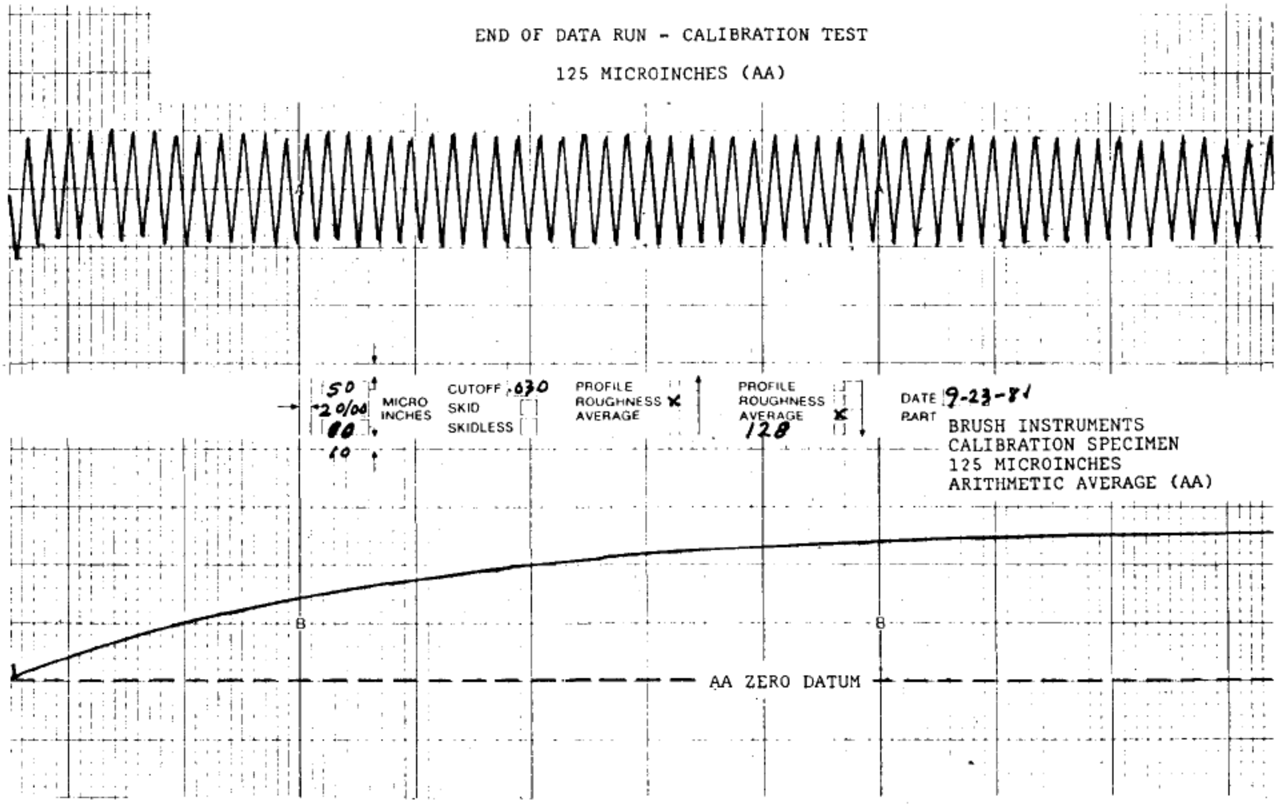

Fig. 4. Graph-plot of surface roughness calibration test.

Table 4. Multiple Regression Analysis

VARIABLE(S) ENTERED ON STEP NUMBER 9.. WXM

		ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
MULTIPLE R	0.79488	REGRESSION	9.	5767656.47765	640850.71974	25.17104
R SQUARE	0.63184	RESIDUAL	132.	3360699.33221	25459.84343	
ADJUSTED R SQUARE	0.60674					
STANDARD ERROR	159.56141					

$F_{.01,9,132} = 2.55$

----------VARIABLES IN THE EQUATION----------

VARIABLE	B	BETA	B STD ERROR	F
AFS	-30.93	-2.42	12.73	5.9
WASH	-243.44	-0.36	66.15	13.5
AFSP	1.75	1.70	1.03	2.9
AXHT	0.34	0.95	0.09	13.3
TXHT	-0.86E-02	-0.87	0.00	10.6
MATL	79.35	0.26	22.13	12.9
CO	-25.18	-0.27	8.35	9.1
COPEDG	58.67	0.18	23.62	6.2
WXM	52.62	0.12	34.29	2.4
(CONSTANT)	1238.41			

--------VARIABLES NOT IN THE EQUATION---------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
POURT	0.02	0.02	0.31	0.0
SIDE	-0.04	-0.03	0.25	0.1
ALLOY	99.99	99.99	0.00	99.9
WT	0.09	0.08	0.35	0.9
SURF	0.02	0.01	0.08	0.0
HARD	-0.01	-0.01	0.47	0.0
SMOLD	0.04	0.04	0.47	0.2
HYDPS	0.92	0.05	0.00	0.4
AXH	99.99	99.99	0.00	99.9
HTSQ	-0.01	-0.01	0.10	0.0
HRDSQ	-0.02	-0.02	0.45	0.1
HARDP	-0.01	-0.01	0.46	0.0
HYDPSF	-0.04	-0.01	0.35	0.0
AFSXHD	-0.00	-0.00	0.92	0.0

F-LEVEL OR TOLERANCE-LEVEL INSUFFICIENT FOR FURTHER COMPUTATION

STATISTICS WHICH CANNOT BE COMPUTED ARE PRINTED AS ALL NINES.

Table 5. Multiple Regression Analysis

VARIABLE(S) ENTERED ON STEP NUMBER 4.. AXHT

MULTIPLE R	0.74434	ANALYSIS OF VARIANCE	DF	SUM OF SQUARES	MEAN SQUARE	F
R SQUARE	0.55405	REGRESSION	4.	5057558.60970	1264389.65243	42.55220
ADJUSTED R SQUARE	0.54103	RESIDUAL	137.	4070797.20016	29713.84818	
STANDARD ERROR	172.37705					

$F_{.01,4,137} = 3.48$

----------VARIABLES IN THE EQUATION--------

VARIABLE	B	BETA	B STD ERROR	F
AFS	-48.05	-3.76	10.63	20.44
WASH	-364.06	-0.54	47.18	59.55
AFSP	3.10	3.02	0.86	12.97
AXHT	0.58E-01	0.16	0.02	6.05
(CONSTANT)	1953.47			

--------VARIABLES NOT IN THE EQUATION-----------

VARIABLE	BETA IN	PARTIAL	TOLERANCE	F
POURT	-0.01	-0.01	0.45	0.0
COPEDG	0.10	0.11	0.59	1.8
SIDE	-0.09	-0.09	0.41	1.0
CO	-0.16	-0.15	0.39	3.1
ALLOY	99.99	99.99	0.00	99.9
WT	-0.05	-0.06	0.54	0.5
SURF	-0.08	-0.06	0.31	0.6
MATL	0.15	0.18	0.61	4.5
HARD	0.10	0.12	0.71	2.1
SMOLD	0.04	0.05	0.77	0.3
HYDPS	-0.47	-0.18	0.06	4.3
AXH	99.99	99.99	0.00	99.9
HTSQ	-0.15	-0.13	0.36	2.5
TXHT	-0.63	-0.20	0.04	5.4
HRDSQ	0.09	0.12	0.69	1.9
WXM	-0.05	0.05	0.53	0.4
HARDP	0.10	0.12	0.70	2.0
HYDPSP	-0.24	-0.16	0.19	3.4
AFSXHD	0.17	0.10	0.15	1.3

STATISTICS WHICH CANNOT BE COMPUTED ARE PRINTED AS ALL NINES.

Several suspect variables; viz. pouring temperature, casting weight, mold versus core surfaces, mold hardness and metal pressure, were not found to be significant in this statistical model.

Pragmatic analysis of the utility of the significant variables, the marginal return on improvement in correlation and experienced judgment resulted in the selection of the multiple regression model derived at step 4 in the "step-wise" analysis of significant variables, Table 5.

A linear sand fineness effect, a linear mold wash effect, a nonlinear sand fineness component and a nonlinear interactive variable of sand fineness and pouring height gave a correlation of 0.744 which explains about 55% (coefficient of determination) of the variation in roughness of the gray iron casting surfaces studied. The dependent variable of surface roughness measurement AA is a function of these four variables and is expressed in a mathematical equation as follows:

$$(AA) = B_0 + B_1(AFS) + B_2(WASH) + B_3(AFSP) + B_4(AXHT)$$

where:

(AA) = surface finish in microinches
B_0 = a constant-intercept value = 1953.47
B_1 = the slope of the variable (AFS) = -48.05
B_2 = the slope of the variable (WASH) = -364.05
B_3 = the slope of the variable (AFSP) = 3.10
B_4 = the slope of the variable (AXHT) = 0.058

The above multiple regression equation for estimating surface finish is expressed geometrically in Fig. 5. The graphic model of surface finish includes extreme height effects at two metallostatic pressure levels of 12 in. and 60 in., mold wash and no mold wash, and both the linear and nonlinear effects of sand fineness.

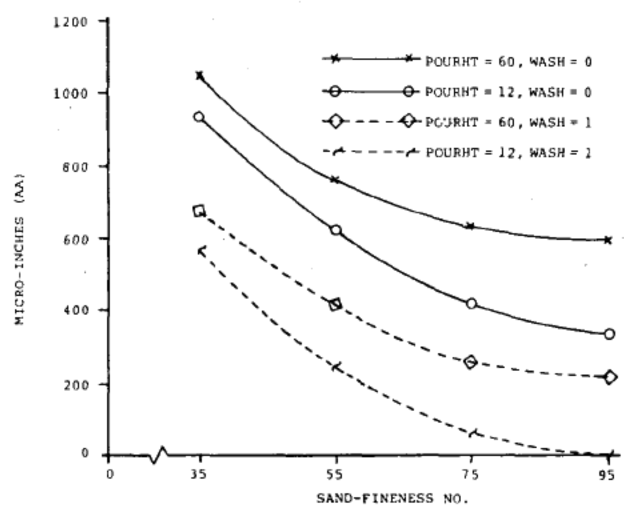

Fig. 5. Casting surface roughness equation.

The ANOVA statistical analysis procedure was used to evaluate the difference between means using "between-groups" and "within-groups" estimates of the population variance.[20] This ANOVA test is used to test the equality of means for two subpopulations of the entire population. In the test qualification of differences of the roughness measurement means for "mold surface" versus "core surface," the variance of the "between-groups" estimate of the population variance is taken as an F-test ratio to the "within-groups" estimate of the population variance, Table 6. The analytical results indicate that there is a very high degree of significant difference between the two means of mold surface roughness and core surface roughness.

Similar ANOVA analysis, Table 7, shows that there is a

Table 6. ANOVA, Mold vs. Core Surfaces

CRITERION VARIABLE RMS
BROKEN DOWN BY SURF

A N A L Y S I S O F V A R I A N C E

VARIABLE	CODE	SUM	MEAN	STD DEV	SUM OF SQ	N
SURF(MOLD SURFACE)	0.	45585.0000	399.8684	171.5990	3327423.0263	(114)
SURF(CORE SURFACE)	1.	17450.0000	623.2143	416.3159	4679610.7143	(28)
WITHIN GROUPS TOTAL (ENTIRE POPULATION)		63035.0000	443.9085	239.1508	8007033.7406	(142)

A N A L Y S I S O F V A R I A N C E

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F.	SIG.
BETWEEN GROUPS	1121322.069	1	**********	19.606	0.0000
WITH FEWER THAN THREE GROUPS, THE RELATIONSHIP IS LINEAR					
WITHIN GROUPS	8007033.741	140	57193.098		

ETA = 0.3505 ETA SQUARED = 0.1228

Table 7. ANOVA, Analysis of Mold Materials

CRITERION VARIABLE RMS
BROKEN DOWN BY MATL

A N A L Y S I S O F V A R I A N C E

VARIABLE	CODE	SUM	MEAN	STD DEV	SUM OF SQ	N
MATL(SHELL SAND)	3.	840.0000	210.0000	128.0625	49200.0000	(4)
MATL(GREEN SAND)	4.	39695.0000	396.9500	169.4315	2841994.7500	(100)
MATL(OIL SAND)	5.	4820.0000	482.0000	384.7597	1332360.0000	(10)
MATL(NO BAKE SAND)	6.	17680.0000	631.4286	358.3058	3466342.8571	(28)
WITHIN GROUPS TOTAL (ENTIRE POPULATION)		63035.0000	443.9085	236.0591	7689897.6071	(142)

A N A L Y S I S O F V A R I A N C E

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F	SIG.
BETWEEN GROUPS	1438458.203	3	479486.068	8.605	0.0000
LINEARITY	1411685.675	1	**********	25.334	0.0000
DEV. FROM LINEARITY	26772.527	2	13386.264	0.240	0.7868
R = 0.3933 R SQUARED = 0.1546					
WITHIN GROUPS	7689897.607	138	55723.896		

ETA = 0.3970 ETA SQUARED = 0.1576

Table 8. ANOVA, Analysis of Mold Wash

CRITERION VARIABLE RMS
BROKEN DOWN BY WASH

A N A L Y S I S   O F   V A R I A N C E

VARIABLE	CODE	SUM	MEAN	STD DEV	SUM OF SQ	N
WASH(NO WASH)	0.	55965.0000	474.2797	267.2936	8359163.7712	(118)
WASH(WITH WASH)	1.	7070.0000	294.5833	73.7787	125195.8333	(24)
WITHIN GROUPS TOTAL						
(ENTIRE POPULATION)		63035.0000	443.9085	246.1759	8484359.6045	(142)

A N A L Y S I S   O F   V A R I A N C E

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F	SIG.
BETWEEN GROUPS	643996.205	1	643996.205	10.627	0.0014
WITH FEWER THAN THREE GROUPS, THE RELATIONSHIP IS LINEAR					
WITHIN GROUPS	8484359.605	140	60602.569		

ETA = 0.2656   ETA SQUARED = 0.0705

significant difference between the average surface roughness for mold materials. These results have a wide discrepancy in "between-groups" results, and variation in sample sizes where only 4 out of 142 observations support conclusions on the shell mix. The main conclusion one can confidently support is that green sand mixes can produce a very good competitive surface roughness and the no-bake sand mixes studied can produce casting surfaces with above average roughness. These findings support the need for further research in this area.

The ANOVA results on the effect of mold wash strongly indicate that a mold wash can significantly reduce roughness of casting surfaces, Table 8.

Comparison of three molding processes, hand molding, jolt/squeeze machine molding and slinger molding indicates that jolt/squeeze operations produce castings with better than average surface roughness, Table 9.

These ANOVA tests, Tables 6, 7, 8, and 9, of main effects for these variables do not indicate significant deviation from linearity for their effects on the average cast surface roughness.

In a separate-allied series of statistical analyses, a t-test[19] was used as an additional test of the significance of differences between the variables of cope surface and drag surface, Table 10; mold wash and no mold wash, Table 11; mold surface and core surface, Table 12; and pressure side and swing side with horizontal casting, Table 13.

The t-test results are summarized as follows:

1) There is no significant indication that drag casting surfaces are rougher than cope casting surfaces, Table 10.
2) There is strong significance for the hypothesis, 1 per cent confidence level, that mold wash reduced casting surface roughness, Table 11. This supports the corresponding significance determined by the ANOVA test results.
3) There is a high significant confidence level of 1 per cent that the mold-casting surfaces were much smoother than the core-casting surfaces, Table 12. This supports the corresponding significance determined by the ANOVA test results.
4) There is a "fair" confidence level of 81 per cent that the swing side surface is less rough than the pressure side, Table 13.

CONCLUSIONS

The objectives of this experiment were achieved. The significance of the main effect of sand grain fineness was shown to be more significant than metal pressure. The findings of Yard and Ekey[9] on the interaction of sand fineness and metal pressure were substantiated. However, the previous results have been refined to show that sand fineness alone has both linear and nonlinear components of significance, independent of metal pressure. This research, and most previous research results, show that sand fineness has a major influence on cast surface roughness. The mold hardness variable, in normal operating ranges of 65-100 on the standard scale, had no significant effect on casting surface roughness. Previous works on Gonya, Ekey, Yard and Goldress[16,13,9] had shown mold hardness as significant, but only at low mold hardness values and with very coarse sand.

The suggestion of Flinn *et al.*[10] to study mold wash was shown to be worthy. Mold wash was quite significant in reducing the roughness of cast surfaces.

The significant result that the singular main effect of metal pressure was not significant, even with 66 in. pressure heads, was interesting, and unexpected. This result conflicts directly with the British work of Bragg.[1] The result does not conflict with previous U. S. research findings, but rather amplifies the nature of interaction among pouring height and other variables. The divergence of findings and opinions suggests a need for further study in this area.

The resulting development of an operational curve to predict cast surface roughness measures for the population environment studied was rewarding.

Table 9. ANOVA, Analysis of Molding Process

CRITERION VARIABLE RMS
BROKEN DOWN BY SMOLD

ANALYSIS OF VARIANCE

VARIABLE	CODE	SUM	MEAN	STD DEV	SUM OF SQ	N
SMOLD (JOLT AND OR SQUEEZER)	1.	35820.000	398.0000	236.0784	4960240.0000	(90)
SMOLD (HAND)	2.	13450.0000	448.3333	271.7641	2141816.6667	(30)
SMOLD (SLINGER)	3.	13765.0000	625.6818	229.8151	1109114.7727	(22)
WITHIN GROUPS TOTAL (ENTIRE POPULATION)		63035.0000	443.9085	243.0497	8211171.4394	(142)

ANALYSIS OF VARIANCE

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F	SIG.
BETWEEN GROUPS	917184.370	2	458592.185	7.763	0.0006
LINEARITY	832229.476	1	832229.476	14.088	0.0003
DEV. FROM LINEARITY	84954.895	1	84954.895	1.438	0.2325
R = 0.3019 R SQUARED = 0.0912					
WITHIN GROUPS	8211171.439	139	59073.176		
ETA = 0.3170 ETA SQUARED = 0.1005					

Table 10. T-Test, Cope vs. Drag Surfaces

T - TEST

T - TEST FOR DIFFERENCE IN MEANS

GROUP 1 - COPEDG EQ 1. (COPE)
GROUP 2 - COPEDG EQ 2. (DRAG)

							POOLED VAR. EST.			SEPARATE VAR. EST.		
VARIABLE		N	MEAN	STD. DEV.	STD. ERROR	F	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.
RMS													
GROUP	1	58	478.36	279.96	36.75	1.06	0.82	-0.32	100	0.74	-0.32	91.28	0.75
GROUP	2	44	496.59	288.33	43.46								

A significant difference in cast surface roughness measurement was found to exist among companies. An understandable variation of management control, quality level of castings, etc., introduced considerable unexplained error variances in the experiment. Statistical data showing this variation in surface roughness of castings produced by the several participating foundries is not presented for proprietary reasons.

Reduction in the breadth of the research design and an increase in the size of the population would be beneficial in additional research in operating environments.

It is a significant result that an experiment subject to extreme error sources in an operating environment can, with statistical research methods, produce productive results.

ACKNOWLEDGMENTS

The author is indebted to several individuals, groups and organizations for major assistance. Appreciation and recognition go to:

1) Five participating foundries: E. L. LeBaron Foundry, Brockton, Massachusetts; Enterprise Foundry, Lewiston, Maine; Vermont Castings, Inc., Randolph, Vermont. H. B. Smith Co., Westfield, Massachusetts; and Cooper-Energy Services, Corry, Pennsylvania.
2) Mr. Robert J. Reilly, District Sales Manager, Whitehead Brothers Company, Florham Park, New Jersey.
3) Dr. Van Bowen, Professor of Statistical Mathematics, University of Richmond, Richmond, Virginia.

Table 11. T-Test, Analysis of Mold Wash

T - T E S T

T - TEST FOR DIFFERENCE IN MEANS

GROUP 1 - WASH EQ 0. (NO WASH)
GROUP 2 - WASH EQ 1. (WITH WASH)

							POOLED VAR. EST.			SEPARATE VAR. EST.		
VARIABLE	N	MEAN	STD. DEV.	STD. ERROR	F	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.
RMS												
GROUP 1	118	474.27	267.29	24.60	13.13	0.00	3.26	140	0.001	6.23	129.0	0.00
GROUP 2	24	294.58	73.77	15.06								

Table 12. T-Test, Mold vs. Core Surfaces

T - T E S T

T - TEST FOR DIFFERENCE IN MEANS

GROUP 1 - SURF EQ 0. (MOLD SURFACE)
GROUP 2 - SURF EQ 1. (CORE SURFACE)

							POOLED VAR. EST.			SEPARATE VAR. EST.		
VARIABLE	N	MEAN	STD. DEV.	STD. ERROR	F	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.
RMS												
GROUP 1	114	399.86	171.59	16.07	5.89	0.00	-4.43	140	0.00	-2.78	29.29	0.009
GROUP 2	28	623.21	416.31	78.67								

Table 13. T-Test, Pressure vs. Swing Side Mold Surfaces

T - T E S T

T - TEST FOR DIFFERENCE IN MEANS

GROUP 1 - SIDE EQ 1. (PRESSURE SIDE)
GROUP 2 - SIDE EQ 2. (SWING SIDE)

							POOLED VAR. EST.			SEPARATE VAR. EST.		
VARIABLE	N	MEAN	STD. DEV.	STD. ERROR	F	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.	T VALUE	D.F.	2-TAIL PROB.
RMS												
GROUP 1	20	357.50	117.87	26.35	1.80	0.21	1.31	38	0.19	1.31	35.13	0.19
GROUP 2	20	314.50	87.87	19.64								

4) The E. C. Robins School of Business, and the Research Committee, University of Richmond, Virginia, for financial assistance in the research.

5) The American Foundryman's Society for confidence, motivation and support.

REFERENCES

1. D. M. Bragg, "An Investigation into the Effects of Increasing Head Pressure on Mould Dilation, Feeding and Surface Finish When Using Common Foundry Moulding Materials," *British Foundryman*, vol 71, pt. 4, p 79-88 (Apr 1978).
2. J. Seifert, F. Fischer, "Horizontal Continuous Casting of Metals With Mould Excited Ultrasonic Waves," *Ultrasonics*, vol 15, no. 4, p 154-158 (Jul 1977).
3. N. F. Ryzhkov, E. C. Gini, "Damping Metal Stream Oscillations During Vacuum Suction Pouring," *Russian Castings Production*, no. 6, p 249-250 (Jun 1976).
4. B. M. Gaisin, "Influence of Gas Pressure in Moulds on Surface Finish of Castings," *Russian Castings Production*, no. 12, p 509-510 (1975).
5. F. P. Sigarev, A. P. Pouldenov, V. I. Kurochkin, V. A. Kansterov, "Production of Silicate-Bonded Sand Shell Moulds on Jolt Moulding Machines," *Russian Castings Production*, no. 3, p 93-95 (Mar 1974).
6. J. E. Parr, "Steel Casting Surface Defects Associated With the Use of Chromite Sand," *AFS Transactions*, vol 81, p 545-547 (1973).
7. R. G. Powell, H. F. Taylor, "Shell Molding for Steel Castings," *AFS Transactions*, vol 66, p 403-408 (1958).
8. G. J. Vingas, A. H. Lewis, "Anionic or Cationic Agents — A Solution to Sand Problems," *AFS Transactions*, vol 64, p 453-458 (1956).
9. R. L. Yard, D. C. Ekey, "Analysis of Factors Affecting Surface Finish of Gray Iron Castings," *AFS Transactions*, vol 64, p 671-678 (1956).
10. R. A. Flinn, W. B. Pierce, F. R. Smith, P. F. Youngdahl, "Dimensional Tolerances and Surface Structure in Various Shell Cast Surfaces," *AFS Transactions*, vol 63, p 143-154 (1955).
11. W. G. Parker, "Improving Surface Finish on Gray Iron Castings," *AFS Transactions*, vol 62, p 82-87 (1954).
12. R. A. Loder, "Establishing Standards for As-Cast Surfaces," *AFS Transactions*, vol 62, p 262-267 (1954).
13. D. C. Ekey, J. E. Goldress, "Statistical Analysis of Factors Affecting Casting Finish," *AFS Transactions*, vol 62, p 605-613 (1954).
14. H. H. Fairfield, J. McConachie, "Effect of Sand Flowability on Casting Surface Finish," *AFS Transactions*, vol 61, p 574-579 (1953).
15. M. E. Gantz, E. M. Gingerich, R. T. Woods, "Magnesium Alloy Permanent Mold and Semi-Permanent Mold Castings," *AFS Transactions*, vol 66, p 502-509 (1953).
16. H. J. Gonya, D. C. Ekey, "Determination of Metal Penetration in Sand Molds," *AFS Transactions*, vol 59, p 253-260 (1951).
17. H. H. Fairfield, J. McConachie, "Casting Surface Finish," *AFS Transactions*, vol 57, p 521-525 (1949).
18. Carson, Bolt, Young, *Production Handbook*, 3rd ed., p 7.48-7.51, Ronald Press, New York, NY (1972).
19. M. Hamburg, *Statistical Analysis for Decision Making*, 2d ed. p 410, Harcourt Brace Jovanovich, Inc., New York, NY (1977).
20. D. R. Anderson, D. J. Sweeney, T. A. Williams, *Introduction to Statistics: An Applications Approach*, p 371, West Publishing Co., New York, NY (1981).
21. K. A. Brownlee, *Industrial Experimentation*, Chemical Publishing Co., New York, NY (1952).
22. W. G. Reichert, D. Wooley, "Factors Which Influence the Surface Quality of Gray Iron Castings," *AFS Transactions*, vol 49, p 212 (1932).