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Application of Cast-On Ferrochrome-Based Hard Surfacing to Polystyrene Pattern Castings

By J. S. Hansen, R. R. Jordan, S. J. Gerdemann, and G. F. Soltau



UNITED STATES DEPARTMENT OF THE INTERIOR



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UNITED STATES DEPARTMENT OF THE INTERIOR

Donald Paul Hodel, Secretary

BUREAU OF MINES

Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Application of cast-on ferrochrome-based hard surfacings to polystyrene pattern castings.

(Bureau of Mines report of investigations : 8942)

Bibliography: p. 33-35.

Supt. of Docs. no.: I 28.23:8942.

I. Hard-facing. 2. Hard-facing alloys. I. Hansen, J. S. (Jeffrey S.). II. Series: Report of investigations (United States. Bureau of Mines) ; 8942.

TN23.U43 [TS227.3] 622s [672.2'5] 84-600297

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT			
°C	degree Celsius	lb	pound
DPH	diamond pyramid hardness	lb/ft ³	pound per cubic foot
ft	foot	min	minute
g	gram	mm	millimeter
g/in ²	gram per square inch	mm ³	cubic millimeter
h	hour	pct	percent
in	inch	s	second
in ²	square inch	vol pct	volume percent
in Hg	inch of mercury (atmospheric pressure)		

APPLICATION OF CAST-ON FERROCHROME-BASED HARD SURFACINGS TO POLYSTYRENE PATTERN CASTINGS

By J. S. Hansen,¹ R. R. Jordan,² S. J. Gerdemann,³ and G. F. Soltau⁴

ABSTRACT

To advance technology that can help conserve critical materials, the Bureau of Mines investigated a cast-on hard-surfacing technique that improves wear resistance and confines alloy additions to wear-prone surfaces. Wear-resistant material in powdered form is applied on a polystyrene pattern, the pattern is embedded in a mold of unbonded sand, and the wear-resistant material is transferred to a casting surface at the time of pouring.

For low-stress abrasion, surfacings derived from high-carbon ferrochrome had higher wear resistance than did commercially available weld-deposited hard facings. The microstructure of the surfacings was typical of hypoeutectic white iron containing M_7C_3 -type carbides. Free carbon added to the ferrochrome powder produced more M_7C_3 carbides than did material contained in surfacings made from ferrochrome alone, and improved the wear resistance. Several white iron powders with greatly reduced chromium contents also produced white iron surfacings containing M_7C_3 carbides. One surfacing derived from white iron powder had wear resistance equal to that of weld-deposited hard facings.

Among the parameters investigated, surfacing thickness was found to have a major influence on solidification, diffusion of elements out of the surfacing, microstructure, and wear resistance. The results of field tests on bucket-wheel excavator teeth and plowshares with cast-on hard surfacing are given.

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INTRODUCTION

The Bureau of Mines is concerned with the conservation of critical materials and improved performance of equipment used in the mining and minerals processing industries. One of the major causes of failure of this equipment is wear. Depending upon the severity of wear, equipment components may last as long as several years or as briefly as a few hours. The high costs involved, in terms of both labor and raw materials, have provided the driving force for many efforts to reduce wear.

Commercially, wear is combated in many ways. The application of wear-resistant coatings to wear-prone surfaces is one way that offers significant advantages. With the exception of manganese steels in specific instances, coatings are the only means available to achieve optimum wear resistance and optimum toughness in the same part because these two mutually desirable properties are inversely related to one another. Through coatings, parts that are made tough by alloying and heat treatment can also be made wear resistant on the surface. In addition, expensive and difficult to form carbide and boride materials can be routinely and economically included within surfacings.

Welding an overlay from material contained in a rod or laid down as a powder is the most widely used technique in commercial practice for applying coatings. During welding, both the part surface and the overlay material melt and fuse to one another, creating a strong metallurgical bond. Weld-applied coatings can be laid over large areas and in heavy thicknesses. Unfortunately, the process is not without limitations and difficulties. Because weld overlays are usually applied by hand, the weld overlay process is time consuming and expensive. Thermal expansion differences between the overlay and

part may cause the overlay to crack, and the heat generated during application may result in harmful residual stresses or loss of heat treatment benefits to the part. Excessive dilution of the overlay by iron from the part or absorption of atmospheric gases during application may reduce wear resistance or cause failure upon impact.

Coatings also are applied by flame and plasma spraying of powdered materials. Such coatings are uniform, and the processes are faster than weld overlaying. On the other hand, the bond strength is weaker than the bond strength of weld-overlaid coatings, and consequently, sprayed coatings will not stand up under impact loading.

This report describes the results of research on a new method of applying wear-resistant coatings. Currently, the method, called cast-on surfacing, is limited to steel castings. Two features are unique: It is performed in conjunction with the process of casting, and it uses polystyrene pattern technology. In the method, a layer of wear-resistant material in powder form is applied to the surface of an expendable polystyrene pattern. After low-temperature drying, the pattern is placed in a flask of unbonded sand. Upon pouring, the pattern vaporizes, and metal fills the cavity. Coincidentally, the molten metal permeates and melts the wear-resistant powder in place. The resulting hard surfacing is metallurgically bonded and can be heat-treated with the casting. Compared with conventional coating processes, cast-on surfacing eliminates several steps and reduces the dangers of residual stress buildup and heat cracking. Although other hard surfacings are under investigation, this report describes characteristics of ferrochrome-based surfacings.

BACKGROUND

The concept of cast-on surfacing of polystyrene pattern castings is a combination of two existing technologies. The first technology, cast-on surfacing, is also known as surface alloying or

cast-in-place hard facing. The second technology, polystyrene pattern casting, is also known as the evaporative pattern casting (EPC) process, full-mold process, or lost-foam process. Only in a

few special applications has commercialization been achieved with either technology.

Cast-on surfacing methods have been attempted by many researchers. Double-pour techniques (1)⁵ are used to make bimetal steel mill rolls with high-chromium alloy outer layers and cores of cast iron. Liquid metal has been cast against preheated solids (2) or sintered compacts (3-6). However, in general, most efforts to mate compacts to castings have suffered from gas arising from binders, erosion, and shrinkage of the compact during and after pouring. Excessive diffusion of compact material into the casting also has been a problem.

Other inventions and studies describe cast-on surfacing processes in which uncompact powder is laid loose or pasted in a mold (7-13) to be assimilated onto the casting surface during pouring. Two research teams in particular (5, 14-16) appear to have been relatively successful. Both teams have applied vacuum to molds to eliminate gas-induced defects, and both have produced well-bonded and defect-free coatings with WC-10 pct Co, chromium carbide, ferromanganese, or ferrochromium. Notwithstanding these successes, the vacuum techniques were never commercialized, perhaps because the procedures were not entirely satisfactory or universal for a wide variety of castings.

Polystyrene pattern casting is the second existing technology that is incorporated into the Bureau's cast-on surfacing technique (17). The process entails pouring metal into an expendable and

consumable polystyrene pattern that is embedded in a flask. The pattern vaporizes, pattern gases exit through the sand, and liquid metal fills the cavity vacated by the pattern. Researchers have partially overcome problems with carbon pickup and gas entrapment (18-24).

Several years after it was patented, polystyrene pattern casting was made more attractive by a patent variance (20), which allowed unbonded sand to be used in place of bonded sand. However, more problems, especially with mold collapse, were created. Vacuum has been used to eliminate mold collapse and to assist in removing gases (25-26).

In summary, previous researchers have not been able to achieve satisfactory results in surfacing castings by cast-on methods. Erosion of powders during pouring, shrink voids in coatings, excessive dilution of coatings by base metal, poor infiltration of base metal into coatings, uneven coating thickness, poor surface finish, and porosity have been some of the problems. Moreover, no binder has been found to hold powder on the surface of molds without giving rise to gas. Steel founders who attempted the polystyrene pattern casting process have not been able to produce castings consistently free of erosion, penetration, carbon pickup, sand drop, and polystyrene residual defects. On the positive side, it has been demonstrated that cast-on surfacing and polystyrene pattern casting are potentially feasible. The use of vacuum has been suggested as a means for relieving many defects in both processes.

PROCESS OF CAST-ON SURFACING WITH POLYSTYRENE PATTERNS

For several reasons, the polystyrene pattern casting process was chosen as a potential means to overcome some of the difficulties that had been experienced by earlier researchers of cast-on surfacing. The process appeared to offer unique advantages because powdered hard-surfacing material in paste or slurry form could

be easily applied to complex shapes and dried before use. If necessary, the patterns could be stored for extended durations. Having no preset parting lines, the patterns could be oriented, gated, and risered so that the powdered hard surfacing would encounter minimal disruption during pouring and solidification. Reduced turbulence during pouring also was possible. Casting the patterns under vacuum was a condition thought to be essential for achieving good bonding of the

⁵Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

surfacing. The application of vacuum to a flask containing a pattern proved relatively simple.

The Bureau cast-on surfacing process consists of several steps that are shown graphically in figure 1. Prior to hard surfacing, patterns are constructed from polystyrene. To minimize gas formation, the polystyrene must have a density between 1.00 and 1.25 lb/ft³, which is lower than that used in most other applications of polystyrene foam. Sprues, runners, gates, and risers can be molded integrally with the pattern or molded separately and joined to one another with a nonaromatic rubber cement. Joints and other fillets are filled with beeswax.

Hard-surfacing material in powdered form is mixed with a small amount of binder and a fluidizer of either alcohol or water and applied to appropriate surfaces of the pattern. Application is done by troweling or by alternately spraying the pattern with binder-fluidizer and dusting the sprayed areas with the hard-surfacing powder. After each alternate application of powder, the excess is shaken off before the next layer of binder-fluidizer is applied. Subsequently, the surfacing

is dried in a forced-air furnace at 45° C for a minimum of 2 h. A pattern with the hard-surfacing material applied to a selected surface is shown in figure 2.

After drying the hard-surfacing material, the entire pattern including the gating system and riser is sprayed with a refractory coating. Refractory coatings can be obtained commercially and contain either zircon or silica powders and small amounts of binders, alcohol, and water. The coatings are highly porous to allow gases to pass. The purpose of the refractory is to improve the surface finish and support the mold cavity after the pattern is vaporized. The refractory also is oven-dried at 45° C for a minimum of 2 h to drive off the volatiles.

A flask that is double walled on all sides and the bottom is used to form the mold. The inside walls have screens to permit the passage of gas into the space between the walls, and the outside walls are vacuum tight. The pattern is placed in the flask (fig. 3), and unbonded sand, such as one having a three-screen distribution and an American Foundrymen's Society (AFS) fineness (27) of 75, is compacted by vibration around

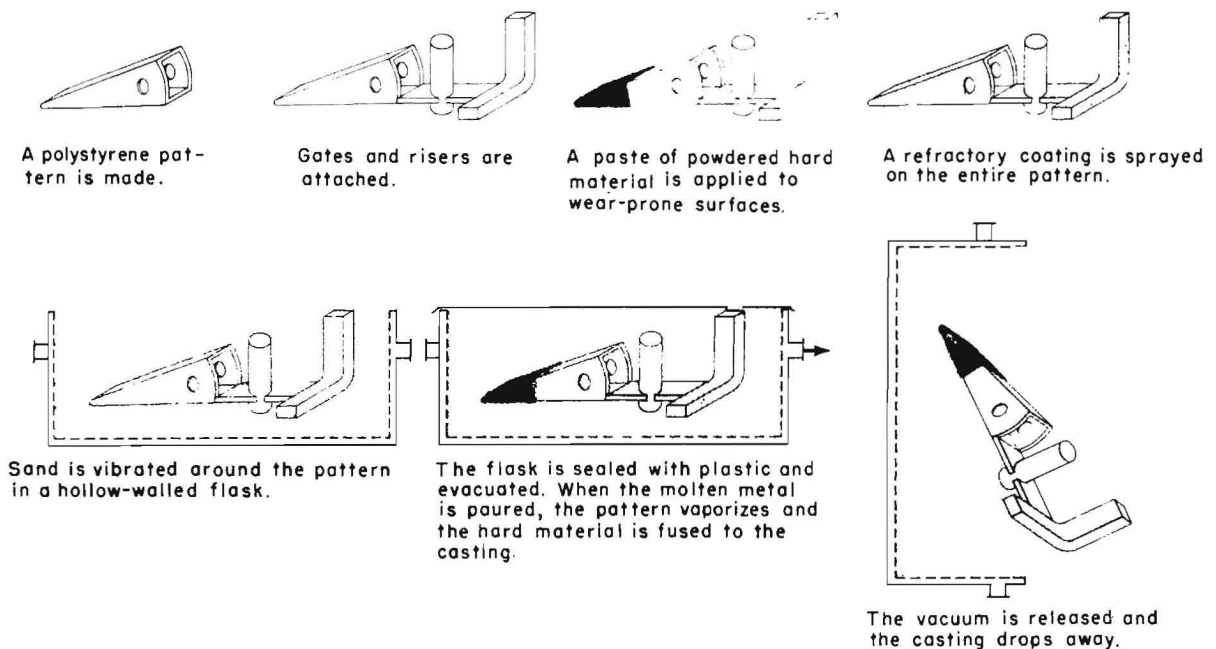


FIGURE 1. - Process steps for applying cast-on surfacings to polystyrene pattern castings.

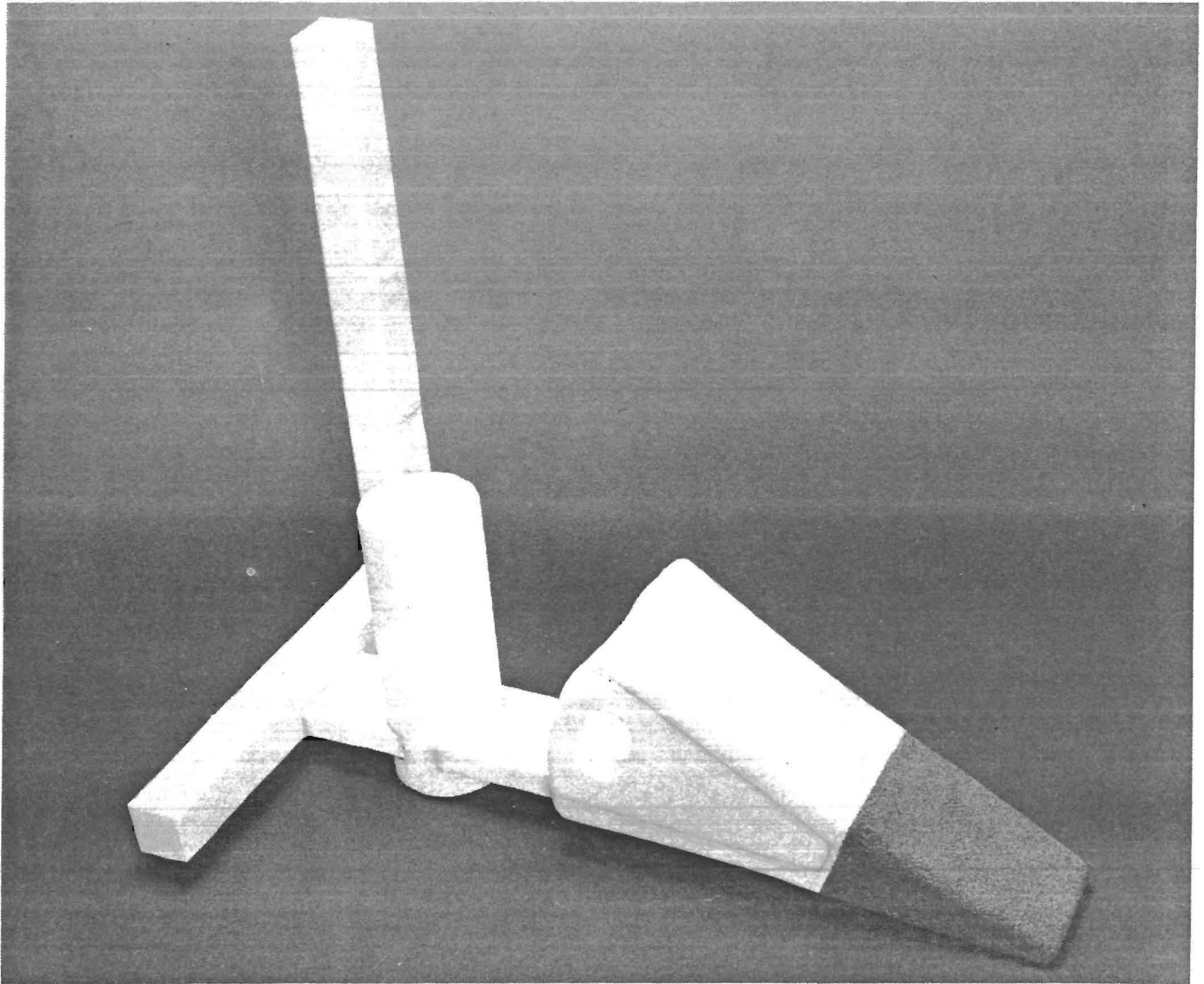


FIGURE 2. - Hard-surfacing material applied to a polystyrene pattern corresponding to the casting wear-prone area.

the pattern. The AFS 75 sand produces the best balance between a superior finish obtainable with a finer sand and improved gas elimination obtainable with a coarser sand.

Generally, the flask is sealed with a sheet of polyethylene plastic over the entire top. Vacuum is applied to the flask prior to and during pouring to provide positive gas elimination, harden the sand, maintain the shape of the molds, and draw the molten metal into the surfacing. Some castings that are located near the top of the flask will cave in

upon pouring as a consequence of the pressure differential between the atmosphere and the evacuated cavity. A stiff plate can be placed under the polyethylene to equalize the effect of the atmosphere and prevent cave-in.

Castings also can be poured in vacuum-process flasks that have double walls but neither a top nor bottom. Polyethylene sheets are used to seal the open ends, and steel reinforcing plates are required just inside both the sheets to prevent cave-in.

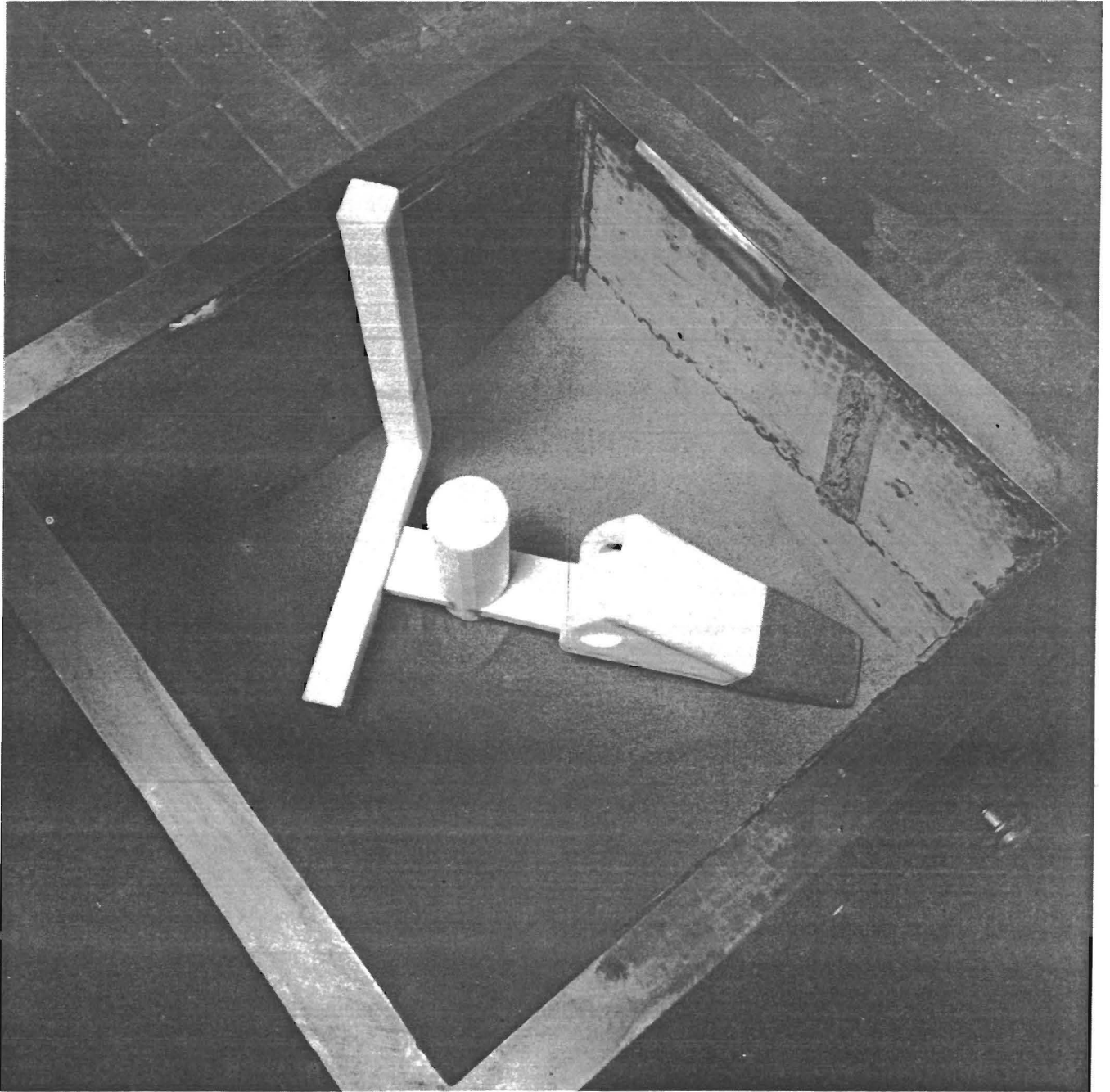


FIGURE 3. - Pattern placed in unbonded sand in double-walled vacuum flask.

EXPERIMENTAL PROCEDURE

Castings for the experiments that are described were poured at 1,555° to 1,620° C under a range of vacuum levels. The vacuum was applied to the flask during the pour and for 10 min thereafter. The pressure during pouring generally increased by 7 in Hg but decreased to the prepour vacuum level thereafter.

Low- and medium-carbon steels were poured directly from a 100-lb-capacity induction furnace into 8- by 12-in pouring basins that were made of sodium silicate-bonded sand and located over the pattern sprues. During pouring, a graphite stopper rod was placed in the basin hole and removed when the metal head was 2 to 3 in. The basin and rod procedure, shown in figure 4, was effective in floating slag to the top of the basin, thus preventing slag defects in the

casting. In addition, without the stopper rod procedure, air was ingested into the casting through a vortex that formed in the sprue. The metal head effectively prevented vortex formation.

Flat-plate castings were removed from the flask after an arbitrarily set time of 2 h. However, other castings have been removed in as little as 1/2 h with no apparent detrimental effect. All castings were entirely cleaned by sandblasting.

Deoxidization of the melts was done with ferrosilicon and aluminum. The silicon content of the steel averaged 0.6 pct, and the aluminum was under 0.2 pct. Melt temperatures were measured with a digital thermocouple just prior to pouring. Flat-plate castings were inclined slightly toward the riser.

DEFINITION OF VARIABLES AFFECTING FERROCHROME CAST-ON SURFACINGS

Commercial high-carbon ferrochrome was one of the first materials to be applied as a cast-on surface. Among its advantages, high-carbon ferrochrome is inexpensive, grindable, normally available at most foundries, compatible with steel, and nonreactive. It melts readily at steel casting temperatures while, for the most part, remaining in place. Upon solidification, it precipitates an abundance of hard carbides that are highly wear resistant. Among its disadvantages are a high strategic mineral content (65-70 pct chromium) and a typically high impurity content (up to 3 pct). As will be shown, these disadvantages were at least partially overcome.

Several experiences and the literature (5, 13, 15-16) suggested that a system combining cast-on surfacing techniques with polystyrene pattern casting would contain many independent and dependent variables. Consequently, statistically designed two- and three-level factorial experiments were used to evaluate individual and interactive effects of the independent variables upon the dependent variables. A list of the relevant variables in cast-on surfacing systems follows:

<u>Independent</u>
Binder type
Binder level
Surfacing particle size
Surfacing thickness
Casting thickness
Pouring temperature
Vacuum level
Powder application technique
<u>Dependent</u>
Surfacing porosity
Casting porosity
Internal porosity
Surfacing roughness
Surfacing contour

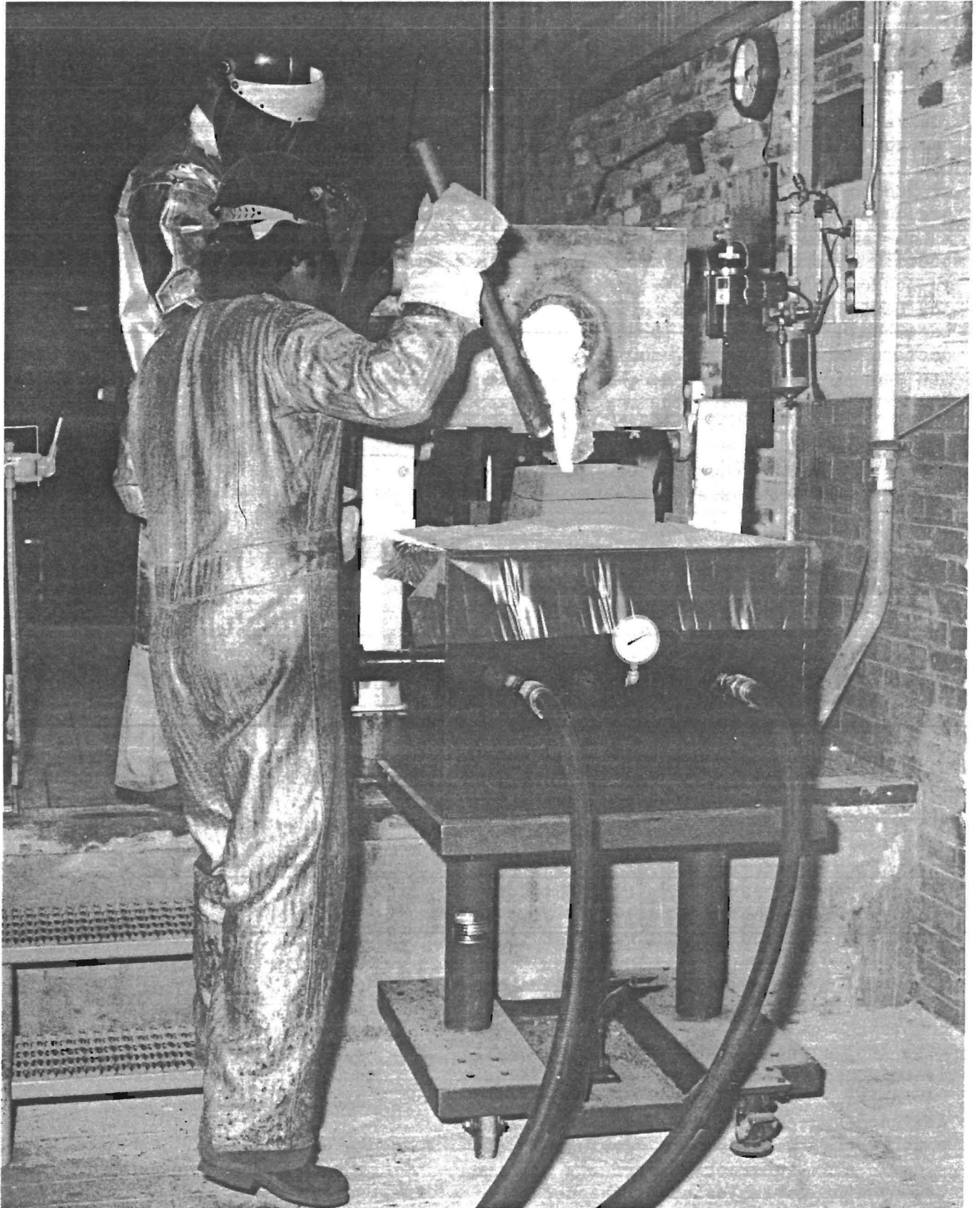


FIGURE 4. - Stopper rod procedure for preventing slag and air from entering gating system and casting.

Proportion of unmelted
surfacing

Proportion of dendrites in
surfacing

Proportion of carbides

Wear resistance

One requirement of factorial experiments is that the dependent variable input must be a number. However, many of the dependent variables in the list of relevant variables are not directly quantifiable without sophisticated and expensive equipment. Despite this limitation, quantifiable assessments can be made of qualitative observations by assigning numerical ratings to the observations. Some of the arbitrariness can be eliminated if guidelines are set up and if independent observations and ratings are done by several persons and averaged.

An evaluation system incorporating such features was used to rate the dependent variables (defects, in most cases) as well as other casting defects that apparently are not related to the application of cast-on surfacings. The system required a minimum of three observers to make independent judgments on the occurrence and severity of the dependent variables. Each observer was required to assign an integer ranking from 1 to 5 for each observation. A guideline that was used to assist the observers in making rankings is given in the appendix.

In general, a ranking of 1 was equivalent to a perfect casting with respect to the defect under observation, while a ranking of 5 indicated the defect was severe enough to scrap the entire casting. Specific defects such as inclusions, small holes, and shrink voids were covered by more detailed guidelines. For dependent variables that were not defects, such as the proportions of dendrites, unmelted surfacing, and carbides, rankings of 1 to 4 were used. These rankings were based on the observer's experience and thus were more subjective than the rankings for defects. In practice, the observers' rankings were usually in exact agreement with one another

and seldom in disagreement by more than one ranking unit.

The number of experiments required at each level of each independent variable was determined by predicting a standard deviation in the results and matching it with a desired, statistically significant difference between consecutive individual results. The statistical equation that defines the relationship is $N = 16\sigma^2/\Delta^2$, where N is the number of experiments, σ is one standard deviation, and Δ is the statistically significant difference between consecutive individual results. Based upon limited experience, a standard deviation of <0.9 was thought to be routinely achievable. The desired difference between individual results was set at a minimum of 1.5. This meant that at least six tests were necessary at each variable level. Thus, for example, if the average ranking for surfacing porosity was 1 at a pouring temperature of $1,580^\circ\text{C}$, and the ranking at $1,600^\circ\text{C}$ was 2.5, the results would be significant provided that the standard deviation in rankings at each temperature was 0.9 or less. If, in the example, the standard deviation was less than 0.9, for instance 0.5, a difference in rankings at each temperature level of 0.7 or greater would be significant.

To carry out the factorial experiments, a casting was designed that allowed three separate samples to be cast simultaneously. Variables such as pouring temperature or vacuum level could not be varied among the three samples on a single casting, but an assortment of other variables, such as the particle size of the surfacing material and the surfacing thickness, could be represented. The three-sample configuration reduced the number of pours and eliminated some of the error that would have been introduced if each sample were made in separate pours.

The three-sample casting consisted of a 6- by 10-in flat plate that was $3/4$ in thick. The samples were located on 1-1/2-in-wide by 6-in-long rectangular-shaped ridges that protruded $1/4$ in from the plate and were separated 1 in from each other. The samples faced down when positioned in the flask. A

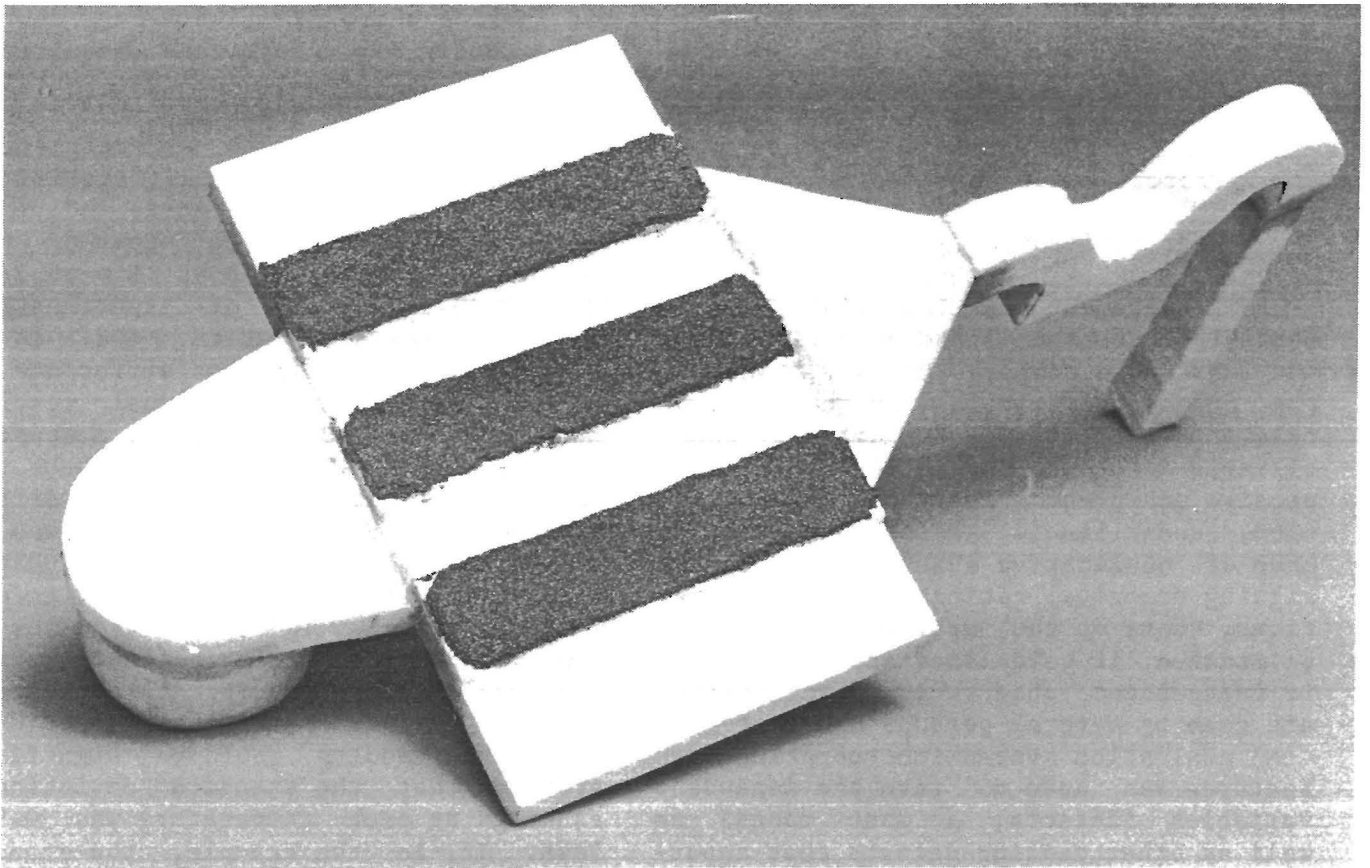


FIGURE 5. - Pattern incorporating sample ridges for three separate surfacings. Powdered surfacings have been applied.

choke-runner-gate ratio of 1:2:4 was used to decrease the turbulence as much as possible and to prevent erosion of the surfacings. A riser was located opposite the gate not only to prevent shrink, but to serve as a trap for unvaporized styrene residues. A pattern with surfacing powders applied to the three samples is shown in figure 5.

Initially, three gating systems with choke areas of 0.23 in^2 , 0.39 in^2 , and 0.56 in^2 were tried on unsurfaced plates to insure adequate filling. Castings produced from the gating system with the 0.56-in^2 choke contained the fewest

defects. This gating system was used for all remaining tests. The flat-plate design was unchanged except for tests in which the casting thickness was altered. For these, the plate thickness was increased to $1\text{-}3/8$ in and $1\text{-}3/4$ in, but the sample protrusion dimensions were kept the same.

The rankings of dependent variables and other results were correlated with independent variables by computer. Surprisingly, good surfacings generally were obtained under a wide variety of conditions.

RESULTS

BINDER TYPE

Seven binders for powders were investigated independently of other variables. The binders were combined with 50 g of minus 65- plus 150-mesh ferrochrome in

the proportions listed in table 1 and were troweled on plate samples to an even thickness. Either water or alcohol was added to each to activate the binder, increase fluidity, and improve application. All but the nonaromatic rubber cement

TABLE 1. - Binders investigated for use with ferrochrome powders

Binder type	Pct used	Minimum drying time, min
Methyl cellulose.....	0.5	100
Nonaromatic rubber cement	.9	50
Polyvinyl acetate.....	.5	150
Polyvinyl butyral.....	.4	25
Sodium silicate.....	1.3	25
Water-based white glue...	.8	150
Zirconium acetate.....	7.1	100

proved easy to spread in the listed proportions, and all formed tight, smooth surfacings when dry. The minimum drying time required for each was determined by heating the samples in an oven at 45° C and weighing each at 5-min intervals until a steady-state weight change was noted. Although 2 h appeared adequate, all samples for casting trials were dried in the oven overnight. While all the binders were compatible with polystyrene, in general those that were alcohol-based were loosened when alcohol-based refractory coatings were applied to the entire patterns and those that were water-based were loosened when water-based refractory coatings were applied.

Multiple samples containing each of the binders were cast at temperatures ranging from 1,560° to 1,580° C and with a vacuum of 25 in Hg or greater. Visually observed porosity rankings of both the surfacings and the unsurfaced portions of the castings ranged from an average of 1 to 2.3 and were not statistically significant. X-ray radiographic rankings of internal defects ranged from 1.5 to 4.3. However, in retrospect, the problem of air entrapment had not been satisfactorily solved, and vortexes were noted in the sprues of three castings during pouring. (The stopper rod technique was introduced to prevent air entrapment after experiments on binder type.) The internal porosity probably resulted from sources other than the surfacing binder because at least one casting containing each surfacing binder combination was porosity free. In addition, blank samples that were used as controls also contained porosity defects.

Methyl cellulose and polyvinyl acetate were judged the most suitable among the binders. Both were relatively inexpensive and easily formulated and applied. Both had a sufficient shelf life and could be kept for several days in sealed containers. Of the two, cellulose was eventually used exclusively because it did not react with the alcohol-based refractory coating that was applied over the pattern and hard surfacing. Alcohol-based refractory coatings also were used exclusively in subsequent tests.

BINDER LEVEL

Upon binder selection, simultaneous tests were done to evaluate the effects of binder level, hard surfacing particle size, surfacing thickness, pouring temperature, and vacuum level. Cellulose was employed as the binder, and levels of 0.3, 0.6, and 1.0 pct of the hard-surfacing weight were investigated. At the same time, the other parameters were varied according to the format listed in table 2.

Increased binder levels produced weak and statistically insignificant increases in all porosity rankings. The data suggest that if porosity was generated in the surfacing, it did not remain there, but migrated into the casting or to the casting top. The dense surfacing layer may have formed an impervious barrier on a substantial portion of the bottom casting surface and impeded the escape of gases from the vaporized pattern. As shown in figure 6A, externally visible porosity on the casting (exclusive of the surfacing) increased with binder level. (The bracketed quantities at each data point indicate ± 1 standard deviation.)

Figures 6B and 6C show that both temperature and vacuum level had a slight, synergistic effect with binder level on casting porosity. A full 30-in-Hg vacuum applied to the flask was more effective than an 8-in-Hg vacuum in pulling off gases from the casting. Also, more gases appeared to have been dissolved and subsequently trapped in castings poured at 1,610° C than at 1,560° C. While the data indicate that porosity increases with binder level, they also

TABLE 2. - Experiments to determine effect of five variables on surfacing integrity with centerpoint checks

(Powder application by trowel, 1-in plate thickness, methyl cellulose binder)

Surfacing thickness, in	Pouring temp, °C	Vacuum level, in Hg	Amount of binder, pct	Surfacing powder size, mesh
3/16	1,580	15	0.6	Minus 65 plus 150.
1/16	1,600	30	1.0	Minus 150 plus 270.
5/16	1,600	30	1.0	Minus 35 plus 65.
1/16	1,600	30	.3	Minus 150 plus 270.
5/16	1,560	8	1.0	Minus 150 plus 270.
1/16	1,560	8	1.0	Minus 150 plus 270.
5/16	1,560	8	.3	Minus 150 plus 270.
3/16	1,580	15	.6	Minus 65 plus 150.
1/16	1,560	30	1.0	Minus 35 plus 65.
5/16	1,560	30	.3	Minus 35 plus 65.
1/16	1,560	30	.3	Minus 35 plus 65.
5/16	1,600	8	.3	Minus 150 plus 270.
1/16	1,600	8	.3	Minus 35 plus 65.
5/16	1,600	8	1.0	Minus 35 plus 65.
3/16	1,580	15	.6	Minus 65 plus 150.

show that if the binder level is kept below 0.3 pct, little damage occurs. Cellulose binders may be decreased virtually to as little as 0.1 pct, at which level no effect will be noticed. Porosity did not increase with surfacing thickness as might be expected considering that, at the same binder level, the total binder in the thickest layer is three times that in the thinnest layer.

SURFACING MATERIAL PARTICLE SIZE

As shown in figure 7A, minus 150- plus 270-mesh powder resulted in a smoother surfacing than did minus 35- plus 65-mesh powder. The effect was more pronounced with 3/16-in-thick surfacings than with 1/16-in-thick surfacings. The thickness of the surfacing was a factor because the ferrochrome did not entirely melt at thicknesses greater than 3/16 in. A full 30-in-Hg vacuum also improved surfacing finish by 15 to 40 pct at the three levels of particle size.

External casting porosity, internal porosity, and external surfacing porosity were also affected by particle size.

Figure 7B shows that the lowest external casting porosity was obtained at an intermediate particle size of minus 65 plus 150 mesh. External surfacing porosity increased only at a fine, minus 150-plus 270-mesh particle size (fig. 7C), probably because surfacing permeability was reduced. A similar result would be evident in a plot of particle size versus internal porosity.

POURING TEMPERATURE

It has been shown (5) that for a given surfacing thickness, an unsatisfactory bond between the surfacing and casting results when certain minimum pouring temperatures and casting section thicknesses are combined. At these minimums, sufficient heat is not provided to the surfacing to nullify the chill effect produced by the surfacing. At an opposite extreme, certain combinations of maximum pouring temperatures and casting section thicknesses logically can be assumed to promote excess diffusion of the surfacing into the casting. Because casting section thickness is usually fixed, the pouring temperature and, to a lesser

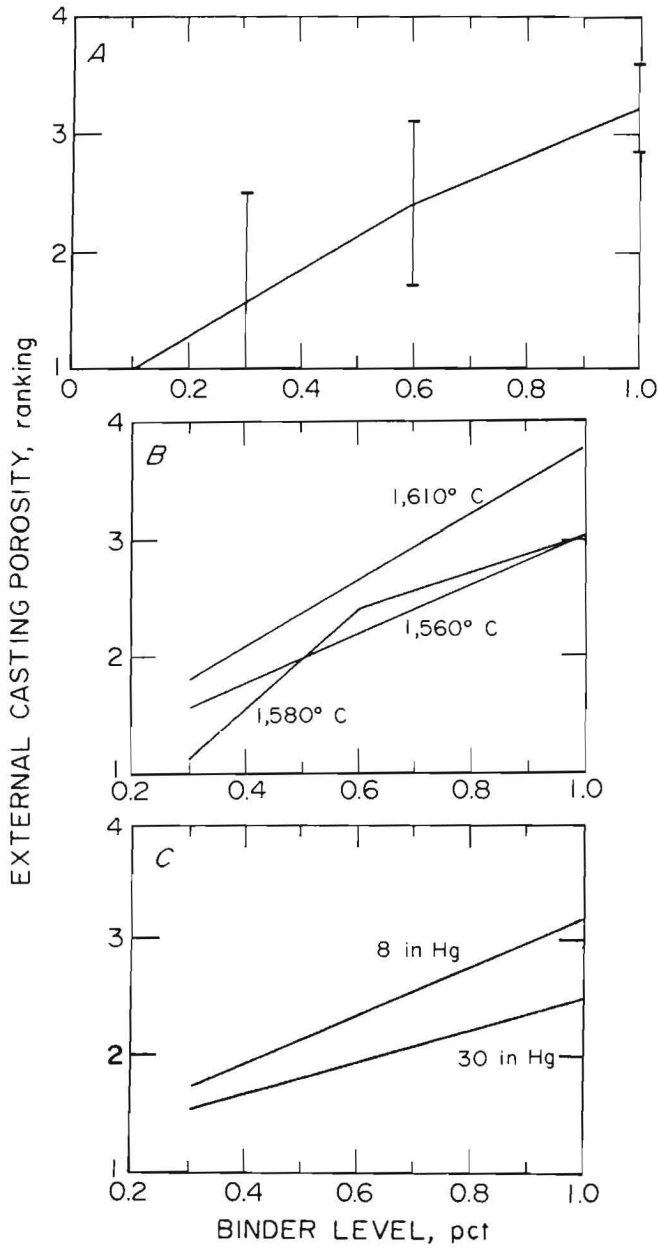


FIGURE 6. - Effect of surfacing binder level. *A*, On external casting porosity (bracketed quantities include one standard deviation); *B*, on external casting porosity at three pouring temperatures; *C*, on external casting porosity at two vacuum conditions.

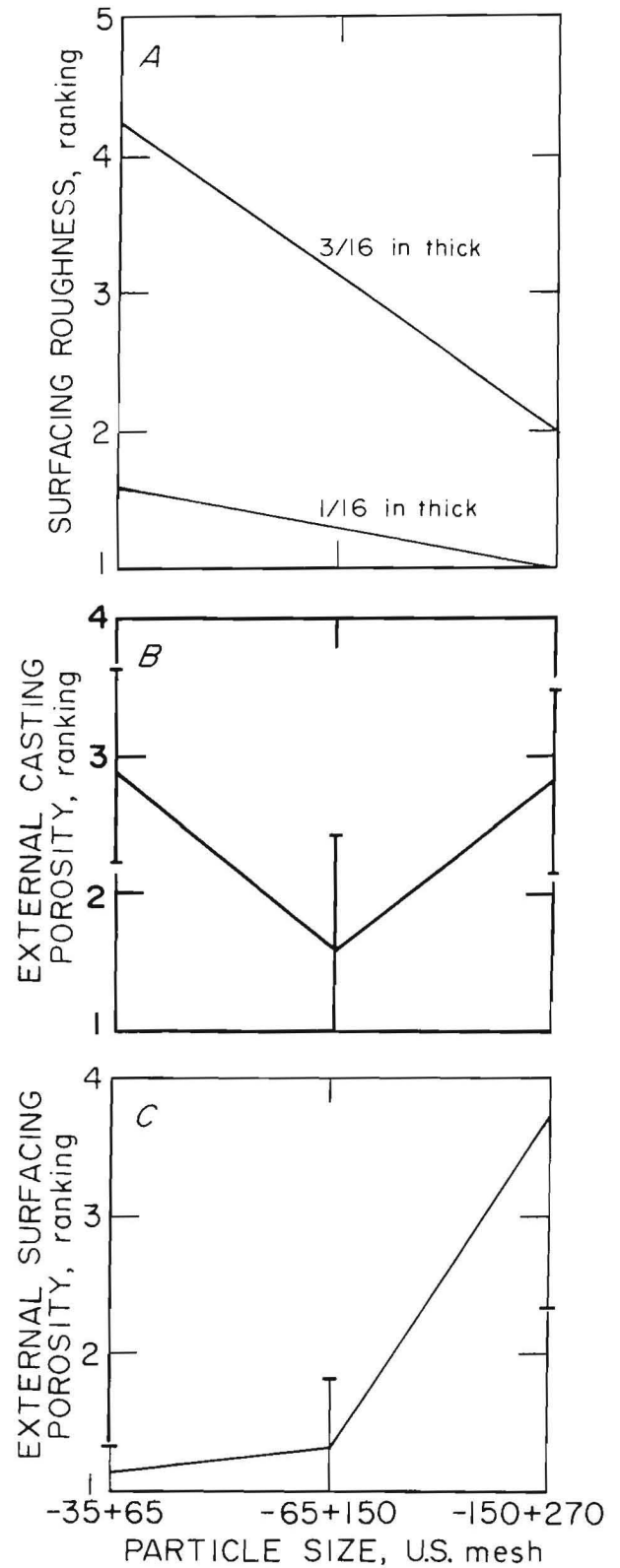


FIGURE 7. - Effect of particle size. *A*, On surface finish at two surfacing thicknesses; *B*, on external casting porosity; *C*, on external surfacing porosity. Bracketed quantities include one standard deviation.

extent, the surfacing thickness, must be optimized to achieve a satisfactory bond quality yet prevent surfacing material from diffusing excessively.

The current investigations indicate that the usable ranges of pouring temperatures and casting section thicknesses are quite broad. The range of thicknesses investigated were from 1 to 1-3/4 in and were well above the minimum predicted thickness (5) would result in poor bonding. Likewise, the pouring temperatures of 1,560° to 1,610° C were well within the range investigated in reference 5. The pouring temperature variations did not affect bond quality or cause surfacing diffusion, although a variety of microstructures resulted (discussed later).

The only notable effect of pouring temperature was produced above 1,580° C and in tandem with a vacuum level of 8 in Hg. The combination caused an increase of 1.67 in the external casting porosity rating. This effect of temperature and vacuum level on external casting porosity is graphed in figure 8. Similar increases were noted for surfacing and internal porosity.

VACUUM LEVEL

Except in combination with higher pouring temperatures, vacuum had no significant effect on any dependent variable. A conclusion that might be assumed is that the vacuum could be dispensed with entirely if a slight increase in porosity could be tolerated. Without

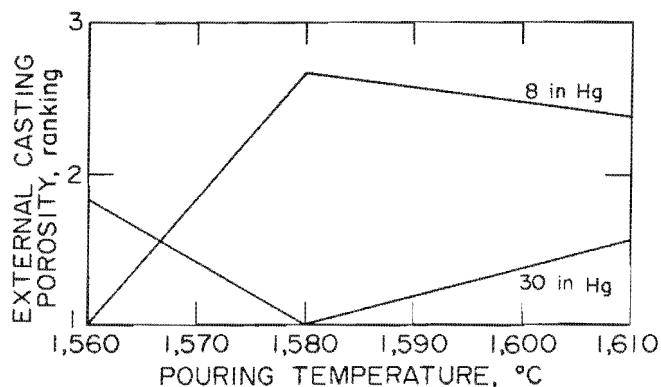


FIGURE 8. - Effect of temperature on external casting porosity at two vacuum levels.

vacuum, a considerable monetary savings would be realized, and pouring problems would be eased. Pouring into an evacuated flask effectively increases the sprue height by an amount equal to the height of a column of liquid steel in an evacuated manometer. When this height, about 52 in, is added to the actual sprue height, the velocity of the metal passing through the choke is at least twice that of metal poured similarly into a flask without vacuum. Some of the vacuum is neutralized by the gases produced from the vaporizing polystyrene, and possibly, the resistance offered by the polystyrene itself is effective in reducing the turbulence. Nevertheless, the net effect of the vacuum is to increase turbulence in the metal entering the mold. Additionally, vacuum creates a vortex in the sprue during pouring, and precautions such as use of the stopper rod must be taken to insure that air is not entrained in the metal.

In practice, the results of eliminating the vacuum are not clear. The flat-plate samples are castable without vacuum. Successful application of wear-resistant surfacings without vacuum assist may be possible in other instances with modifications to variables such as gating. However, surfacings have been applied to the entire exterior of more intricate patterns, and without vacuum, these surfacings did not fuse to the castings. The implication is that vacuum is necessary for at least some applications.

APPLICATION PROCEDURE

Application technique was investigated, along with surfacing thickness, casting thickness, pouring temperature, and vacuum level, in a second set of factorial experiments that is shown in table 3. Of the two application procedures (troweling of premixed paste, and alternate spraying and dusting of binder and powder), improvements of 25 to 50 pct were noted in the ratings for most properties with the latter, but the data were widely scattered and statistically insignificant. Notwithstanding the data scatter, the spraying and dusting procedure demonstrated that hard-surfacing powders may

TABLE 3. - Experiments without centerpoint checks to determine effect of five variables on surfacing integrity

(Minus 65- plus 150-mesh ferrochrome surfacings, methyl cellulose binder at <0.3 pct of surfacing weight, 30-in-Hg vacuum level except as noted)

Pouring temp, °C	Surfacing thickness, in	Casting thickness, in
TROWEL APPLICATION		
1,560 ¹	1/8	1
1,560 ¹	1/8	1
1,610 ¹	1/8	1
1,610 ¹	1/8	1
1,560	1/8	1
1,610	1/8	1
1,560	1/8	1-3/8
1,560	1/8	1-3/8
1,610	3/16	1-3/8
1,610	1/8	1-3/8
1,610	3/16	1-3/8
1,560	3/16	1-3/4
1,560	1/8	1-3/4
1,560	3/16	1-3/4
1,610	1/8	1-3/4
1,610	3/16	1-3/4
1,610	1/8	1-3/4
SPRAY APPLICATION		
1,560 ¹	1/8	1
1,610 ¹	1/8	1
1,560	1/8	1
1,560	1/8	1
1,610	1/8	1
1,610	1/8	1
1,560	3/16	1-3/8

¹8-in-Hg vacuum level.

be applied to patterns by automated methods without loss of properties.

CASTING THICKNESS

As noted previously in the discussion of pouring temperature effects, casting thickness effects upon the integrity of the surfacing and bond below a certain minimum thickness were predicted (5). In this study, the casting thicknesses of 1 to 1-3/4 in were above minimum of reference 5 and did not affect integrity. However, surfacings that were applied to 1- and 1-3/4-in-thick patterns in equal amounts appeared almost twice as thick on the heavier casting than on the lighter casting, although the total thickness of the surfacing plus casting remained constant. The apparent thickness increase

thus was caused by migration of the surfacing materials inward. Unexpectedly, the interface, though shifted inward, remained distinct. The effect of this dilution of the surfacing upon wear most likely would be negative.

SURFACING THICKNESS

Surfacing thickness was the most important variable controlling surfacing quality. It dictated the microstructure, which in turn determined wear resistance. As surfacing thickness was increased, less and less of the powdered ferrochrome melted.

At 1/16-in thickness, the entire surfacing was melted. Coincidentally, the microstructure was highly dendritic, and few carbides were noticeable. A



FIGURE 9. - Microstructure showing dendrites and interdendritic carbides typical of thin (1/16-in), chromium-rich, white iron surfacings derived from ferrochrome (upper). The steel of the casting has a Widmanstätten structure (lower) (X 50).

microprobe analysis showed that infusion of iron from the casting into the surfacing was substantial. The microstructure formed was characteristic of hypoeutectic, chromium-rich white irons typically having 2 to 2.5 pct C and ~15 pct Cr with Cr:C ratios of 5.5 to 7.5. Such white irons have about 25 vol pct carbides. A representative microstructure of a thin ferrochrome cast-on surface is shown in figure 9. The light, dendritic areas contained 1.5 to 2.0 pct C and 11.2 to 11.9 pct dissolved Cr, and the interdendritic carbides contained 7.7 pct C, 38.6 pct Fe, and 53.7 pct Cr. The carbon content of the carbides was below the 9.0 pct C content of an ideal M_7C_3 -type carbide.

Chromium levels in the casting metal adjacent to the interface ranged from 0.1 to 0.6 pct, indicating that metal diffusion from the 1/16-in-thick surfacing into the casting was insignificant. In contrast, carbon levels in the casting metal next to the interface ranged from 0.5 to 1.4 pct. Because the diffusion coefficient of carbon is a thousand times greater than that of chromium, some of the enhanced carbon at the interface can be assumed to have originated from the surfacing. However, carbon levels at the surfaces of steel castings made from polystyrene patterns are characteristically higher than castings made by other processes (23). Thus, the polystyrene pattern must also be considered a carbon source.

Figure 10 indicates the effect of increasing surfacing thickness. As the surfacing thickness was increased, the proportion of unmelted ferrochrome powder increased (fig. 10A), the proportion of dendrites in the surfacing decreased (fig. 10B), and the proportion of carbides also increased (fig. 10C). In contrast with thinner surfacings, dendritic structures disappeared entirely at a thickness of 3/16 in. As indicated by the first three samples in table 4, the chromium content of the surfacing carbides increased from 53.7 to 77.6 pct while the chromium in the surfacing matrix increased from 11.2 to 20.4 pct. With increasing thickness, the diffusion of carbon from the surfacing across the

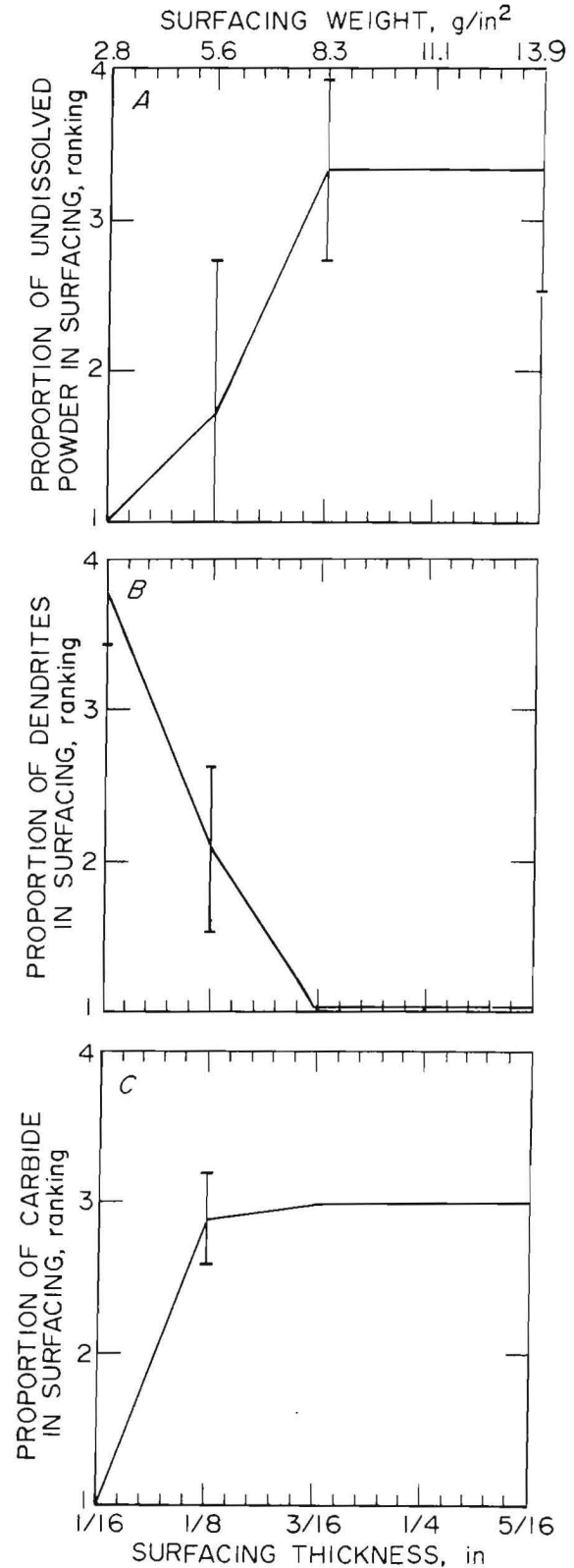


FIGURE 10. - Effect of increasing surfacing thickness. A, Unmelted ferrochrome powder increase; B, dendritic microstructure decrease; C, carbide particle increase. Bracketed quantities include one standard deviation.

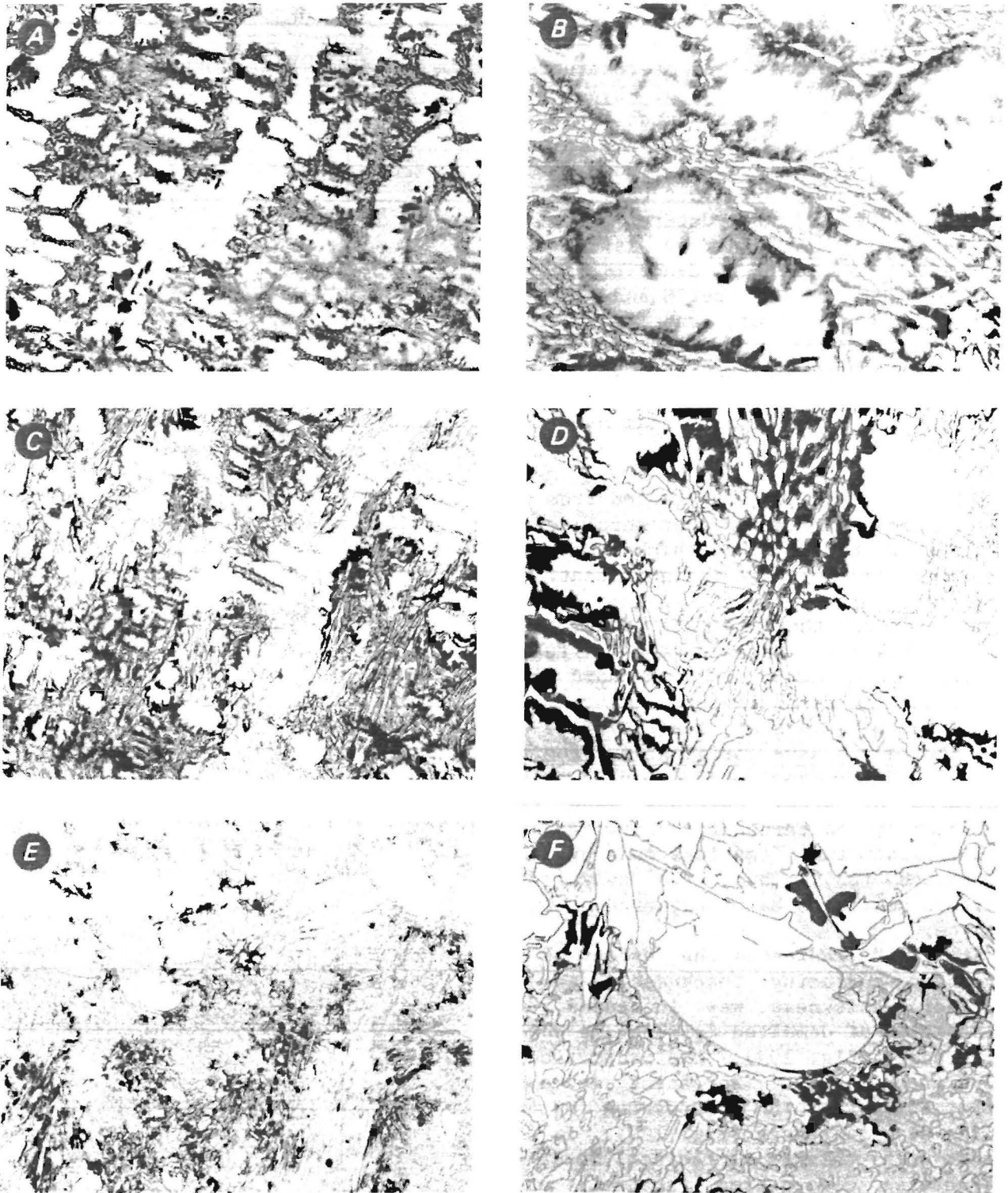


FIGURE 11. - Microstructures of surfacings at three thicknesses. *A*, 1/16 in thick (X 100); *B*, 1/16 in thick (X 400); *C*, 1/8 in thick (X 100); *D*, 1/8 in thick (X 400); *E*, 3/16 in thick (X 100); *F*, 3/16 in thick (X 400).

TABLE 4. - Effect of surfacing thickness on surfacing composition and hardness

Surfacing thickness, in	Surfacing material	Microstructure description	Constituent	Composition, pct		Micro-hardness, DPH ¹
				Cr	C	
1/16.....	{ Commercial ferrochrome. ²	} Highly dendritic	{ Carbide.	53.7	7.7	³ 559
			{ Matrix..	11.2-11.9	1.5- 2.0	456
1/8.....	...do. ²	Medium dendritic	{ Carbide.	66.2	9.0	1,619
			{ Matrix..	17.9-19.1	1.4- 2.9	610
3/16.....	...do. ²	Nondendritic....	{ Carbide.	77.6	8.6	1,644
			{ Matrix..	20.4	0.0	491
1/8.....	{ No. 2 custom ferrochrome. ⁴	} Highly dendritic	{ Carbide.	45.7	8.5	³ 555- 567
			{ Matrix..	9.7	1.8	459
1/8.....	{ No. 3 custom ferrochrome. ⁵	} Medium dendritic	{ Carbide.	42.0	9.5	³ 699
			{ Matrix..	8.8-10.8	1.4- 2.8	375- 551
5/16.....	{ Commercial ferrochrome ² with exothermic addition.	} Highly dendritic	{ Carbide.	53.0	10.0	³ 924
			{ Matrix..	11.7	2.1	355

¹100-g load, 25-s test duration. ²66.9 Cr, 6.4 C.

³Carbides too small for indenter; reading includes portion of matrix.

⁴58 Cr, 8.4 C. ⁵54 Cr, 7.8 C.

interface into the casting slowed. The carbon content of the carbides approached the ideal M_7C_3 composition, and the carbides were larger and harder. With higher levels of chromium and carbon in the matrices, the hardness of the matrices likewise increased. Figure 11 shows the progression of microstructures with the three thicknesses. At the 3/16-in thickness, the carbides adjacent to the interface were small and sometimes elongated; toward the outer surfacing, the carbides were large and blocky. The nondendritic outer microstructure was similar to hypereutectic chromium white irons with 30 to 35 pct carbides.

Metallographic observations of the ferrochrome-surfaced samples also revealed a large number of inclusions that were located near the surfacing-casting interface. The inclusions, containing Mg-Al silicates and chromite, floated upward to the interface while the surfacing was molten. The inclusions resulted from the high impurity content that is allowable in commercial ferrochrome grades that are intended primarily as additions to steel. During the initial stages of wear, the inclusions would not be expected to be detrimental. However, after the surfacing wore to the depth of the relatively soft inclusions, wear resistance would suffer.

In summary, the wider implications of increased surfacing thickness are that chill is more significant, solidification time is shorter, chromium and carbon migration out of the surfacing is less, and carbide precipitation and microconstituent hardness are greater. Thin surfacings are dendritic and hypoeutectic while thick surfacings are nondendritic and eutectic or hypereutectic. The ultimate effect of surfacing thickness, through its influence on microstructure and carbide proportion, is of course upon wear resistance.

The low-stress abrasion resistance of surfacings was measured in a dry-sand, rubber-wheel test according to ASTM standard G-65, procedure B (28). The test is performed by pressing a sample against a revolving rubber wheel as a standard type of sand is passed between the wheel and sample. If all conditions are kept the same from test to test, the volume losses from sample surfaces, as an indication of wear resistance, may be directly compared with one another. The results of the dry-sand, rubber-wheel tests were averaged from two identical tests and are shown in table 5.

The first three samples listed in table 5 were surfaced with commercial ferrochrome in progressive thicknesses from 1/16 to 3/16 in. Volume losses to the

TABLE 5. - Dry-sand, rubber-wheel abrasion test results on cast-on surfacings derived from ferrochrome powders

Surfacing material	Surfacing thickness, in	Dry sand test vol loss, mm ³
Commercial ferrochrome ¹	1/16	21.58
Do. ¹	1/8	14.37
Do. ¹	3/16	9.87
No. 2 custom ferrochrome ² ...	1/8	8.97
No. 3 custom ferrochrome ³ ...	1/8	10.97
Commercial ferrochrome ¹ with 0.1 g C/g FeCr added.....	1/16	5.69
Commercial ferrochrome ¹ with exothermic addition.....	5/16	8.49
NiHard I.....	NAp	13.19
1080 (water-quenched).....	NAp	29.10
Weld-applied hard surfacing.	~3/16	11.3

NAp Not applicable. Commercially available part cast entirely of specified material.

¹66.9 Cr, 6.4 C.

²58 Cr, 8.4 C.

³54 Cr, 7.8 C.

sample surfaces ranged from 21.58 mm³ on the thinnest surfacing to 9.87 mm³ on the thickest surfacing. The table 4 and 5 data on commercial ferrochromes show a definite correlation between wear resistance and surfacing thickness, namely, that wear resistance is improved as surfacing thickness is increased.

Unfortunately, surfacing thickness cannot be increased infinitely to achieve ever higher wear resistance. Surfacing quality is optimum at thicknesses of about 1/8 to 3/16 in. At greater thicknesses, steel from the casting is not sufficiently drawn into the surfacing and melting is not always complete. Porosity is more apparent, and wear resistance deteriorates. The effect of thickness on surfacing and casting porosity is shown in figures 12A and 12B, respectively. The high porosity at the 1/16-in thickness could not be linked to any of the measured variables.

Roughness and contour were other properties that deteriorated with surfacing thickness. Roughness, as a measure of texture, increased slightly between surfacing thicknesses of 1/16 to 1/8 in and substantially at surfacing thicknesses over 3/16 in. Because surfacings over 3/16 in did not melt or fuse, the outer

portions flaked off, leaving a gritty finish.

Surfacings over 1/16 in thick experienced gross shrinkage that reached

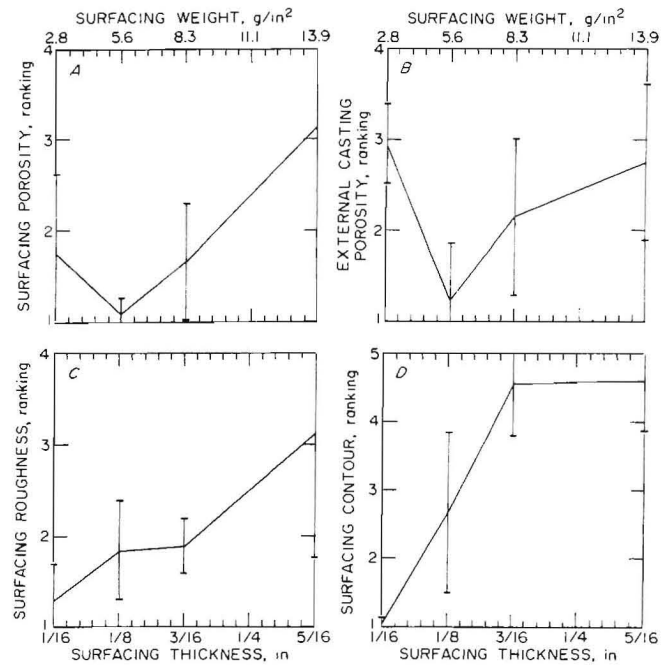


FIGURE 12. - Effect of surfacing thickness. A, On surfacing porosity; B, on external casting porosity; C, on roughness; D, on contour. Bracketed quantities include one standard deviation.

maximum severity at 3/16-in thickness. The shrinkage, in most cases, was characterized by a dip from the plane of the sample running the length of the midline.

This deviation from flatness was termed contour. The effects of thickness on roughness and contour are shown in figures 12C and 12D.

COMPOSITIONAL VARIATIONS ON FERROCHROME SURFACINGS

Two custom-melted ferrochromes were obtained that were more refined in comparison with the commercial ferrochrome. The custom-melted ferrochromes were applied to flat-plate samples. Figure 13 shows X-ray radiographs taken of 1/8-in-thick sections of surfacings made with one of the custom, low-impurity ferrochromes and with commercial ferrochrome. The figure shows that nearly total elimination of inclusions was achieved with the custom-melted ferrochrome.

Perhaps more significant than the elimination of inclusions, the custom ferrochromes contained higher carbon levels than the commercial ferrochrome, although

reduced chromium. At thicknesses of 1/8 in and less, the higher carbon produced surfacings with a high proportion of carbide. One of the custom ferrochrome surfacings is shown in figure 14A. The increase in carbide can be contrasted with the carbide contained in commercial ferrochrome surfacings shown in figures 11A and 11B.

The carbides, although finely divided, contained high levels of carbon. From table 4, it is seen that the number 2 and 3 custom ferrochromes, at 1/8-in thickness, contained carbides with 8.5 and 9.5 pct C, respectively, which compare with the carbide carbon content of commercial

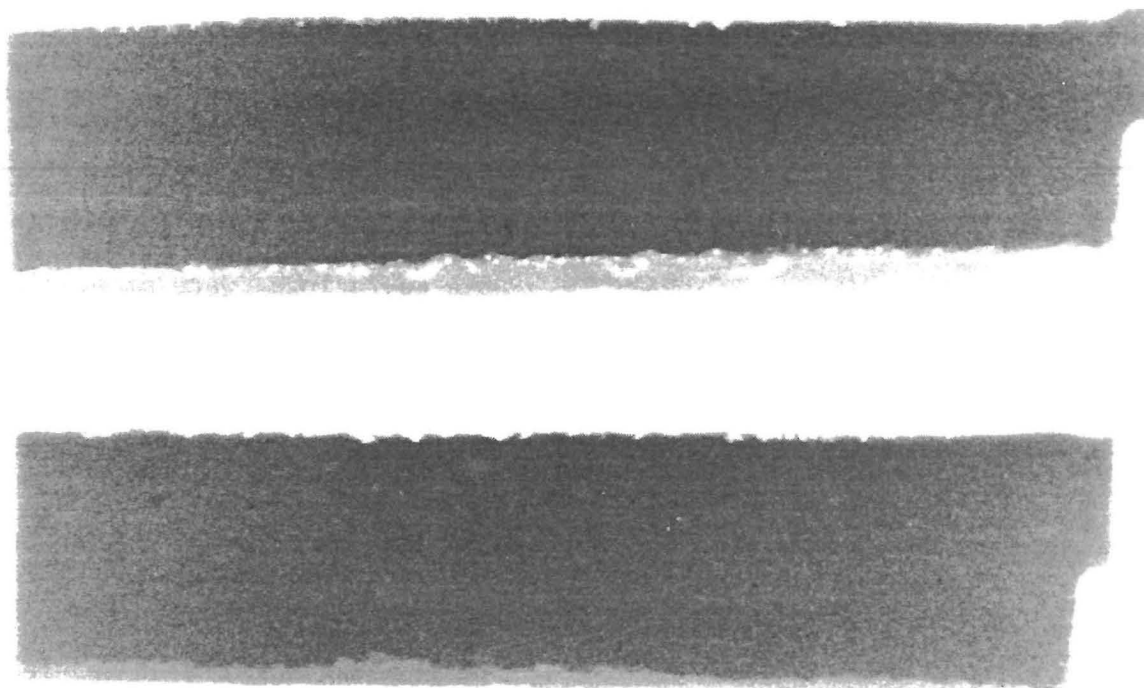


FIGURE 13. - X-ray radiographs showing inclusions at the surfacing-casting interface of samples surfaced with commercial ferrochrome (upper) and number 2 low-impurity custom-melted ferrochrome (lower).

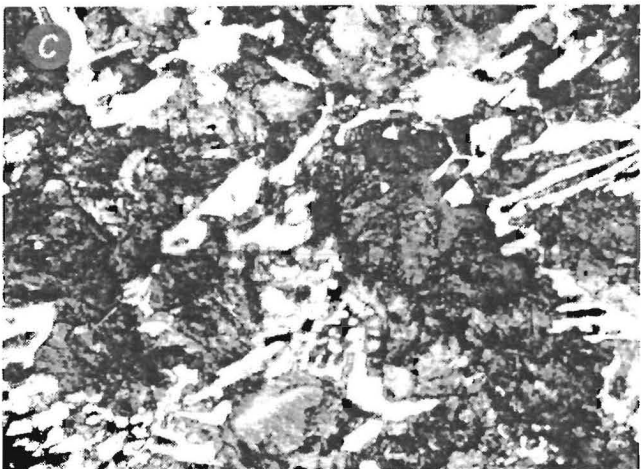
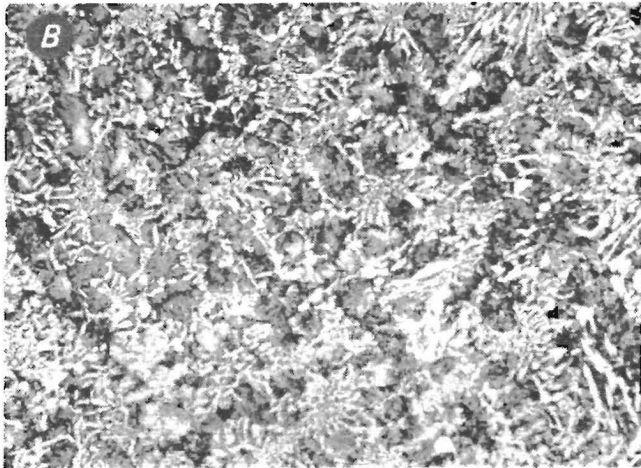
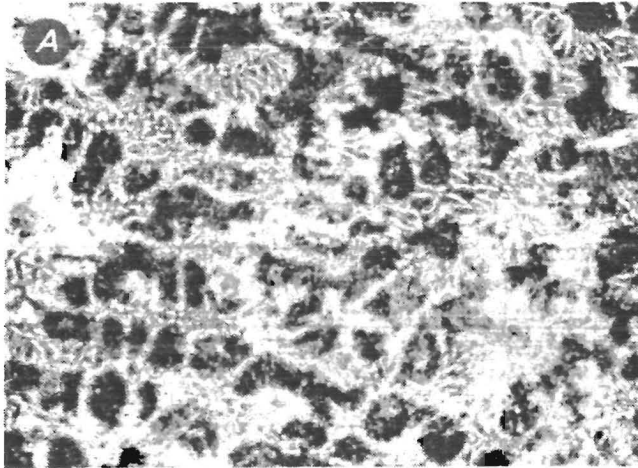


FIGURE 14. - Microstructure of number 3 custom-melted ferrochrome and commercial ferrochrome with 0.1 g added carbon per gram of ferrochrome. *A*, 1/8 in thick number 3 ferrochrome (X 100); *B*, commercial ferrochrome with added carbon (X 100); *C*, commercial ferrochrome with added carbon (X 400).

ferrochrome at a greater thickness of 3/16 in. The chromium contents of the matrices were between 8.8 and 10.8 pct. As shown in table 5, the increased carbide content and carbide hardness of the number 2 and 3 custom ferrochromes produced dry-sand, rubber-wheel abrasion volume losses for 1/8-in-thick surfacings of 8.97 and 10.97 mm³, respectively. The losses represent improvements of 24 to 38 pct over commercial ferrochrome surfacings at the same thickness and are again comparable to commercial ferrochrome surfacings of 3/16-in thickness.

Nearly the identical microstructure that was obtained with the custom-melted ferrochromes was also obtained from commercial ferrochrome powder to which free carbon was added. At a level of 0.1 g of C to 1.0 g of ferrochrome, the interdendritic carbide precipitation in a 1/16-in-thick surfacing was slightly greater than that of either custom-melted ferrochrome. The elevated carbon ferrochrome microstructure is shown in figures 14*B* and 14*C*. The dry-sand, rubber-wheel abrasion test volume loss of 5.69 mm³ generated from this surfacing and noted in table 5 was a 37-pct improvement over that of the number 2 custom ferrochrome.

Additional improvements were made to commercial ferrochrome surfacings that were over 5/16 in thick. By applying an outer layer of exothermic material consisting of 33 pct Al and 67 pct Fe₂O₃, the surfacings were smooth and dendritic upon solidification. Notwithstanding the longer solidification time available, carbon diffusion out of the surfacing did not occur to a large extent, and as shown in table 4, the carbide contained 10.0 pct C. The higher carbon produced a carbide microhardness of 924 DPH in comparison with a hardness of 559 DPH for carbides in a similar dendritic structure from a 1/16-in-thick surfacing. The increased carbon content of the carbide and heightened microhardness led to a dry-sand, rubber-wheel abrasion test volume loss that was lower than that resulting from all other ferrochrome surfaces except the one enhanced with free carbon additions. This volume loss, noted in table 5, was 8.49 mm³.

STEEL AND WHITE IRON SUBSTITUTES FOR FERROCHROME

Inasmuch as diffusion of steel into ferrochrome surfacings yielded white iron structures on solidification, the possibility of forming white iron and carbide-containing structures directly from white iron or steel powders was investigated. The compositions and dry-sand, rubber-wheel abrasion test results on selected 1/16-in-thick surfacings are listed in table 6.

The steel compositions formed void-marked surfacings, with porosity rankings of 4 and 5. One steel, with the composition Fe-0.7C-4Cr-4Ni-14Mn-0.04Si, resulted in a single-phase structure of low hardness (DPH 603). A second steel, with the composition Fe-0.7C-7Cr-1.5Ni-1.3Mo-0.9Mn-0.9Si, resulted in a fine bainitic structure with a blocky, fairly hard second phase (DPH 975). Neither steel was deemed suitable for wear testing because of the porosity.

Several white iron compositions with carbon contents ranging from 2.3 to 4.6 pct and chromium contents ranging from 2.2 to 26.5 pct produced cast iron microstructures with few if any carbides. All surfacings except one were smooth, porosity free (ranking of 1), well melted, and dendritic. The exception contained 14.0

pct W and 8.0 pct V and had a 3.7 porosity ranking. Two compositions that typified the group were selected for dry-sand, rubber-wheel abrasion tests. The volume losses for the two, shown in table 6, were 17.63 and 21.39 mm³. The volume loss for commercial ferrochrome at an equivalent thickness was 21.58 mm³.

An exceptional white iron with the composition Fe-5C-21Cr-8.5Cb-9Mo-0.3Mn-0.6Si produced an exceedingly low (11.70 mm³) volume loss in the dry-sand, rubber-wheel test. The microstructure of the white iron, shown in figure 15, consisted of a matrix of gray iron with 3.1 pct C; large blocky carbides with 5.2 pct C, 9.7 pct Mo, and 81.0 pct Cb; and semicontinuous interdendritic carbides with 9.2 pct C, 34.3 pct Cr, 43.1 pct Fe, and 13.2 pct Mo. Both carbide phases had high hardnesses--the columbium(niobium)-rich phase measured 702 to 1,055 DPH and the chromium-rich phase measured 903 to 1,391 DPH.

Unlike the ferrochrome surfacings, free carbon additions to the Cr-Cb-Mo white iron surfacing reduced the proportion of carbides. In the only abrasion test on the enhanced-carbon white iron, the surfacing wore through and did poorly.

TABLE 6. - Compositions of white iron and steel cast-on surfacings and selected dry-sand, rubber-wheel abrasion test results

Compositions, pct	Dry-sand test vol loss, mm ³	Remarks
Fe-0.7C-4Cr-4Ni-14Mn-0.04Si.....	NT	Single phase, DPH = 603.
Fe-0.7C-7Cr-1.5Ni-1.3Mo-0.9Mn-0.9Si.....	NT	Second phase, DPH = 975.
Fe-2.3C-10.9Cr-4.8V-1.3Mo-0.3Mn-0.3Si.....	NT	Few carbides.
Fe-3.2C-2.2Cr-3.9Ni-0.7Mn-0.6Si.....	NT	No carbides.
Fe-3.2C-20Cr-1Ni-1.5Mo-1Cu-0.8Mn-0.5Si.....	NT	Few carbides.
Fe-3.9C-5Cr-14W-8V-1Ti-13Mn.....	NT	Fine precipitate, overall DPH = 430.
Fe-3.1C-22Cr-1Ni-2Mo-0.8Mn-0.6Si.....	17.63	Few carbides.
Fe-4.6C-26.5Cr-3.4Mo-0.4Mn-1.3Si.....	21.39	Few carbides, overall DPH = 833.
Fe-5C-21Cr-8.5Cb-9Mo-0.3Mn-0.6Si.....	11.70	Cb-Mo carbides plus M ₇ C ₃ carbides.
Fe-7.5C-21Cr-6.1Cb-9.9Mo-0.3Mn-0.6Si.....	NT	Less carbide than above.
Fe-10C-21Cr-6.1Cb-9.9Mo-0.3Mn-0.6Si-0.9Al.....	52.69	Wore through.
Cr ₇ C ₃	15.68	Highly dendritic.

NT Not tested.

However, a better wear factor might be expected had the surfacing been thick enough and not worn through.

The last surfacing listed in table 6 was made with minus 50- plus 100-mesh Cr_7C_3 powder. The resulting surfacing was dendritic except at the outer surface, which retained a thin layer of intact Cr_7C_3 particles. The particles were porous, and the surfacing was rough. Additional M_7C_3 carbides with 9.5 pct C and 55.4 to 57.0 pct Cr were reformed interdendritically from the portion of

surfacing that dissolved. The hardness of the reformed carbides was 634 to 852 DPH, and the hardness of the intact Cr_7C_3 particles was 1,960 to 2,300 DPH. The volume loss in the dry-sand, rubber-wheel test was 15.68 mm^3 . No advantage would likely be gained by using carbide powders in place of less expensive ferrochrome or white iron powders because higher rates of wear could be expected as soon as the carbide particles were lost. Controlling the dissolution of the carbides also would be difficult.

FIELD TRIALS⁶

Many researchers have been at least partially successful in applying cast-on surfaces to small, idealized samples that are oriented and gated preferentially to avoid drawbacks such as erosion of the surfacing during pouring and drift during solidification. Problems arise with larger and more complex configurations. Through the use of the polystyrene pattern casting process, the disadvantages

inherent in other casting processes can be avoided because positioning is more flexible and turbulence is reduced.

Several demonstrations were conducted to show the versatility of the Bureau's cast-on surfacing process and the advantages of using polystyrene patterns in the technique. Ferrochrome surfacings were successfully applied to small jaw crusher plates, 4-in ball valves, and the inside diameter of a 3- by 8-in cylinder. Cross sections of the three shapes are shown in figure 16. Additionally, bucket-wheel excavator teeth and plowshares were surfaced and installed in operating equipment for side-by-side comparisons with existing components.

⁶The authors appreciate the assistance of T. Braaten, assistant maintenance supervisor, Washington Irrigation and Development Co., Centralia, WA, for the field testing of bucket-wheel excavator teeth; and L. Wells, Jefferson, OR, for the field testing of plowshares.

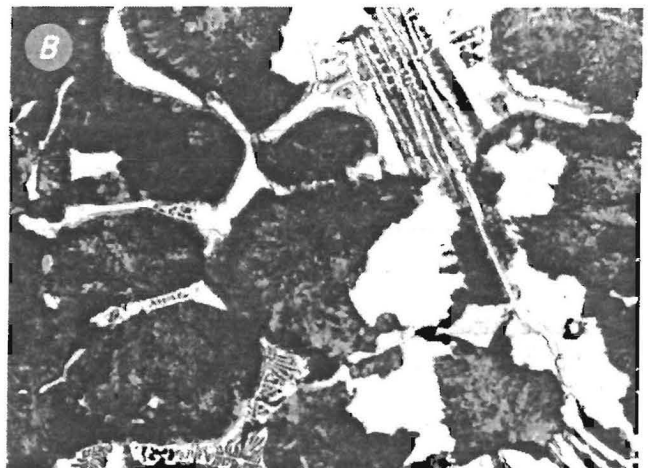
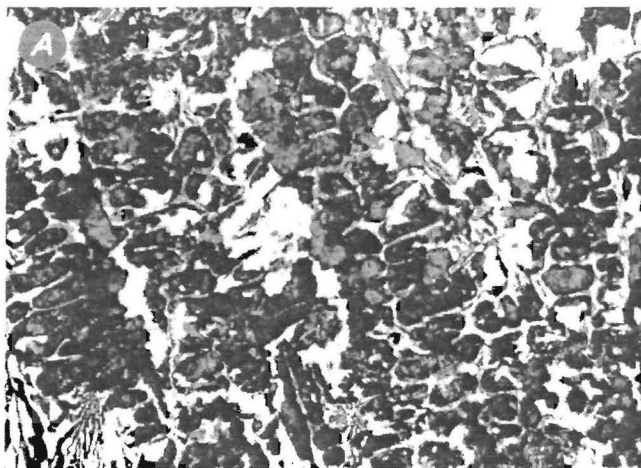


FIGURE 15. - Cast iron microstructure of cast-on surfacing with the composition Fe-5C-21Cr-8.5Cb-9Mo-0.3Mn-0.6Si. A, 1/16-in-thick surfacing (X 100); B, light-colored blocky phase is Cb rich, light-colored stringy phase is Cr rich (X 400).

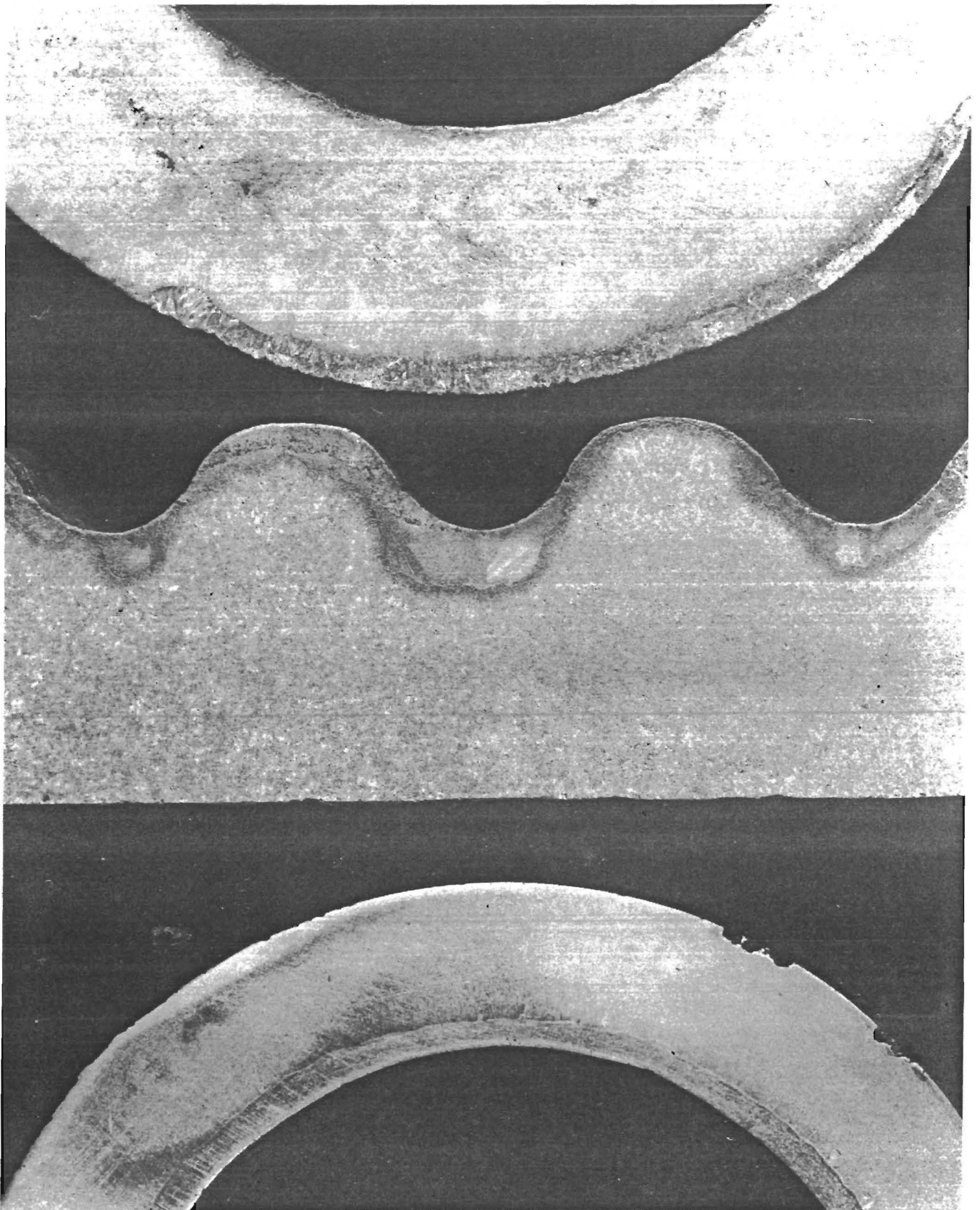


FIGURE 16. - Cross sections of a 4-in ball valve (top), 6-in crusher plate (middle), and 3-in cylinder (bottom) showing ferrocchrome cast-on surfacings.

BUCKET-WHEEL EXCAVATOR TEETH

Bucket-wheel excavators are used to dig overburden, coal, and ores at mines and to transfer stockpiled ores at shipping points and smelters. In operation, the wheel, which is oriented vertically, is driven into an ore body or earthen face. As the wheel rotates, buckets attached to the wheel circumference remove large volumes of material and transfer them to a conveyor belt that is located immediately at the back of the wheel. Each bucket is fitted with several teeth that assist in cutting the face and protecting the bucket edges. Bucket wheels can be over 50 ft in diameter.

A bucket-wheel excavator is used to remove a 100-ft thickness of claylike overburden at a coal mine in Centralia, WA. The wheel has eight buckets, similar to the one shown in figure 17, with nine

teeth per bucket. Originally, the mine used unfaced teeth that were made with a medium-carbon steel (Fe-0.3C-1Mn-0.8Si-1.3Cr-0.4Ni-0.3Mo). The maximum life of each tooth was four 8-h shifts. Recently, the maximum was improved 10 times by weld-rod hard facing done at the mine by mine personnel.

To field test the Bureau's surfacing process, the entire outside surfaces of two teeth were surfaced by the cast-on technique with the number 2 custom ferrochrome and the Fe-5C-21Cr-8.5Cb-9Mo-0.3Mn-0.6Si white iron alloy to a thickness of about 1/16 in. The base metal of the ferrochrome-surfaced tooth had the composition Fe-0.2C-0.4Mn-0.3Si-0.9Cr-0.9Ni-0.1Mo, and the white-iron-alloy-surfaced tooth had the composition Fe-0.2C-0.2Mn-0.5Si-1Cr-1Ni-0.2Mo. A pattern with gates, runners, sprue, and core is shown (upside down for



FIGURE 17. - One of eight buckets of a bucket-wheel excavator at a Centralia, WA, coal mine. Nine teeth are fitted on the edge.

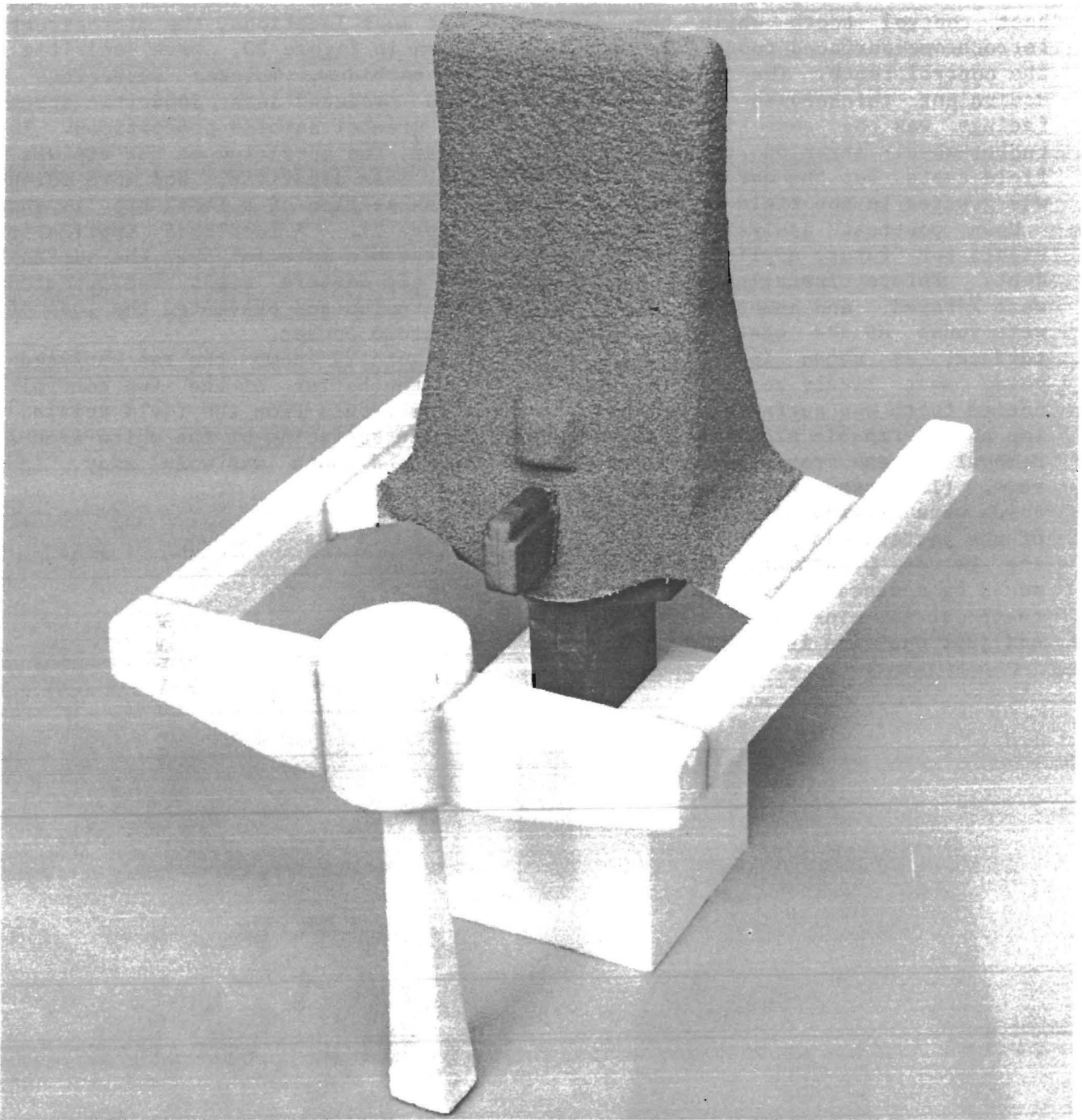


FIGURE 18. - Bucket-wheel excavator tooth pattern with surfacing powder applied to outside.

photographic purposes) in figure 18. The teeth were heattreated at 875°C and oil quenched.

The teeth were installed in identical corner positions on successive buckets along with two weld-rod hard-faced control teeth. The wear of each tooth was assessed by noting the loss in its

length. After 31 shifts of operation, the custom-ferrochrome-surfaced tooth lost 2 in of length, and the white-iron-alloy-surfaced tooth lost 1/2 in. In comparison, the control teeth lost 1-1/4 and 1-1/2 in. In terms of length then, the white-iron-alloy-surfaced tooth registered a 60-pct improvement over the

best control tooth while the custom-ferrochrome-surfaced tooth did worse than the control teeth. The ranking order for equivalent thicknesses of the two surfacings was the same in the dry-sand, rubber-wheel abrasion tests as in the field tests, but the margin of difference was greater in the field trials.

Upon posttest analysis, several insights for future applications were evident. Before installation, the teeth were X-rayed, and numerous small voids were found at the casting-surfacing interface, as shown in figure 19. The voids most likely resulted because the entire tooth was surfaced, thereby creating an impermeable shell that impeded the removal of gas from the vaporizing pattern. (In tests done subsequently, the voids were eliminated when only one side of the pattern was surfaced, thus allowing better breathing. This practice would be acceptable because currently the teeth at the mine are not turned over, and just one side is subjected to wear.)

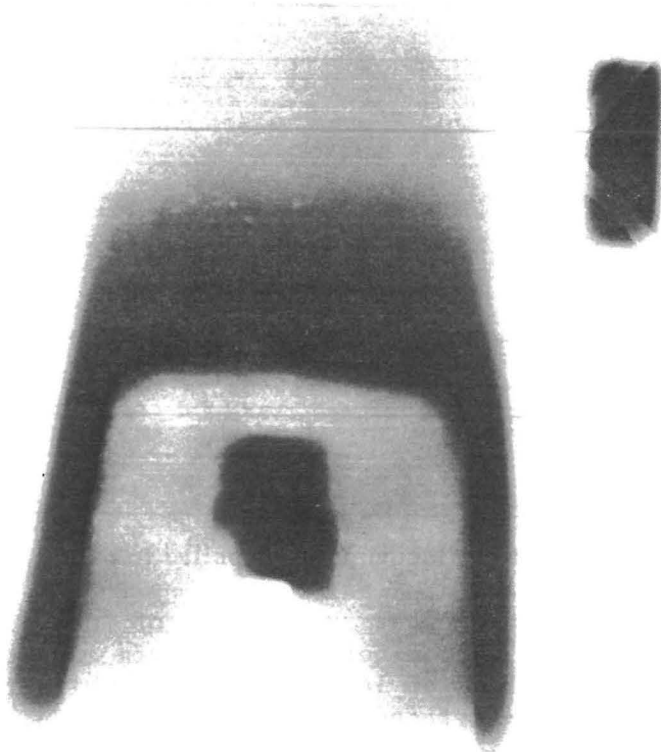


FIGURE 19. - Radiograph of bucket-wheel excavator tooth showing small voids at casting-surfacing interface.

At most locations, the microstructures, shown in figure 20, were dendritic with few carbides. Thicker surfacings would have produced less dendritic structures and greater carbide proportions. In contrast, the surfacing on the tip was thinner, less dendritic, and more porous. A cross section of a tooth tip is shown in figure 21. A localized application of exothermic material over the surfacing on the tip corners might have promoted better fusion and prevented the loss of ferrochrome powder.

Figure 22 shows the two surfaced teeth and the better of the two control teeth after return from the field trials. Much of the surfacing of the white-iron-alloy-surfaced tooth was worn away. In areas

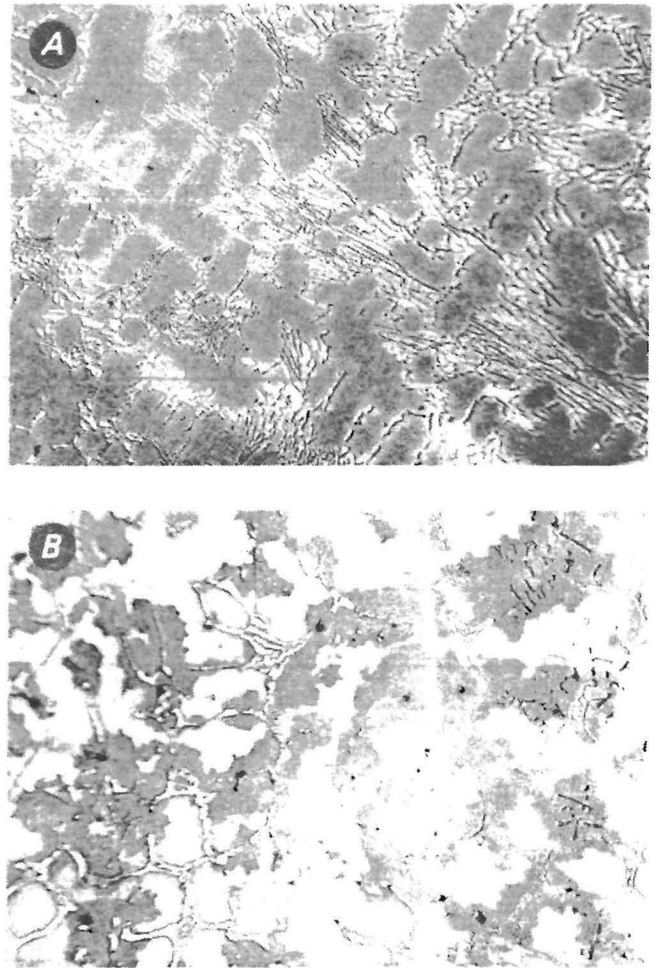


FIGURE 20. - Microstructure of number 2 custom ferrochrome (A) and white iron alloy (B) surfaces from bucket-wheel excavator teeth used in field trials (X 100).

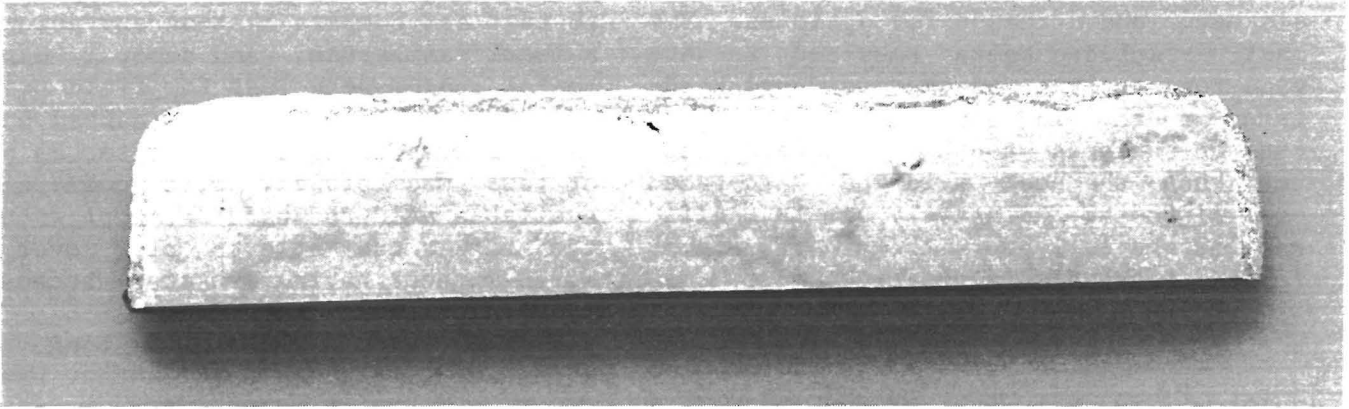


FIGURE 21. - Cross section of bucket-wheel excavator tooth tip showing ferrochrome surfacing along outside edge.

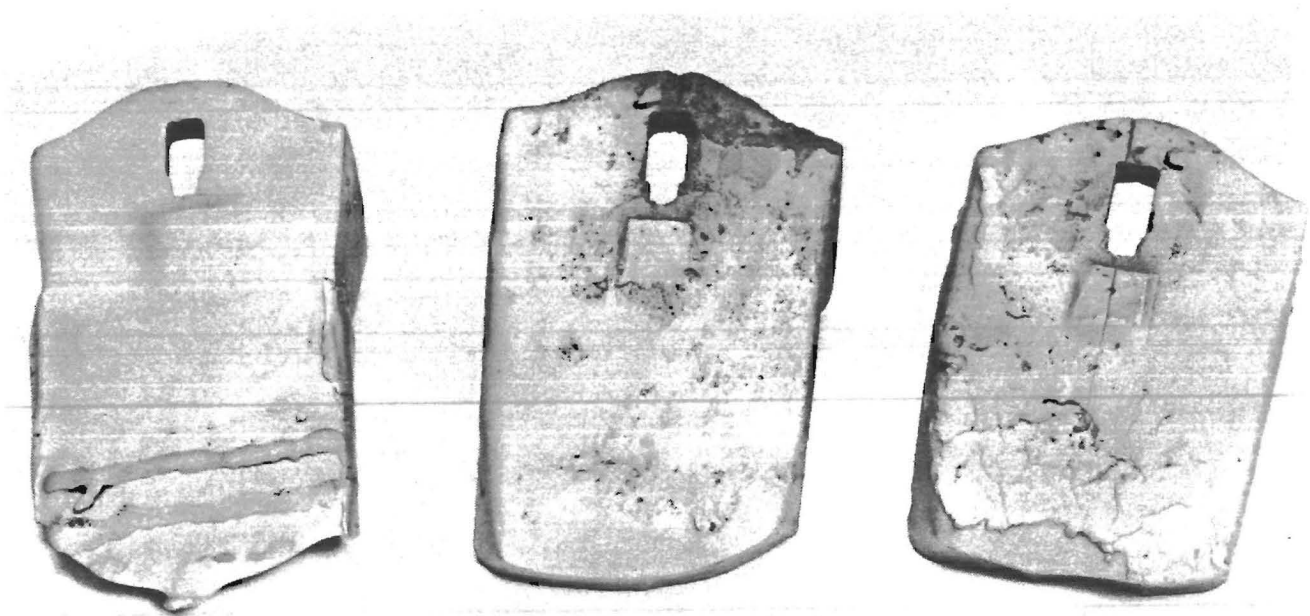


FIGURE 22. - Bucket-wheel excavator teeth after field trials at Centralia, WA, coal mine. Left, weld-rod hard-faced control tooth; middle, Fe-5C-21Cr-8.5Cb-9Mo-0.3Mn-0.6Si composition white iron alloy cast-on-surfaced tooth; right, number 2 custom ferrochrome cast-on-surfaced tooth.

where a thin layer of surfacing remains, the interfacial voids that were noted on the X-rays are evident. The voids provided sites for wear initiation and were obviously undesirable. It appears that the tooth was removed at the optimum time. Had it remained in service longer without a surfacing for protection, wear would have been accelerated.

Figure 22 also reveals numerous cracks in the surfacing of the number 2 custom-ferrochrome-surfaced tooth. The sharp

edge between the surfacing and the casting near the tip indicates the cracks were instrumental in surfacing failure. Some of the cracks were evident after heat treatment, suggesting the heat treatment requires optimization. The large crack that nearly bisects the entire tooth is continuous through to the inside cavity and is the result of an ill fit between the tooth and tooth adaptor on the bucket. A greater shrinkage allowance on the cavity core is the remedy.

In total, the bucket-wheel field trials have shown reason for optimism. The cast-on-surfaced teeth remained in service for as long as the weld-rod hard-faced teeth. In the one instance, a cast-on-surfaced tooth sustained less wear than the best weld-rod hard-faced control tooth. Relatively simple modifications should improve tooth performance. Further tests are in progress.

PLOWSHARES

Plowshares are made of wrought steel and most likely will never be cast commercially. However, the low-stress abrasion that occurs in plowing is similar to the low-stress abrasion that occurs in

many mining environments. An opportunity to test and compare cast-on surfacings at a local farm arose, and several experimental shares were cast for field trials. The sandy soil at the farm caused unsurfaced shares to wear out after 25 acres or less was plowed. With commercially available weld-rod hard-faced plowshares, the farmer was able to plow over 150 acres without having to stop because of plowshare wear.

Plowshares are about 2 ft long, 4 in wide, and 1/2 in thick. Shares are affixed to the bottoms of each of five blade assemblies like the one shown in figure 23. The shares make the initial contact with the soil and protect the remainder of the blade. The leading edge

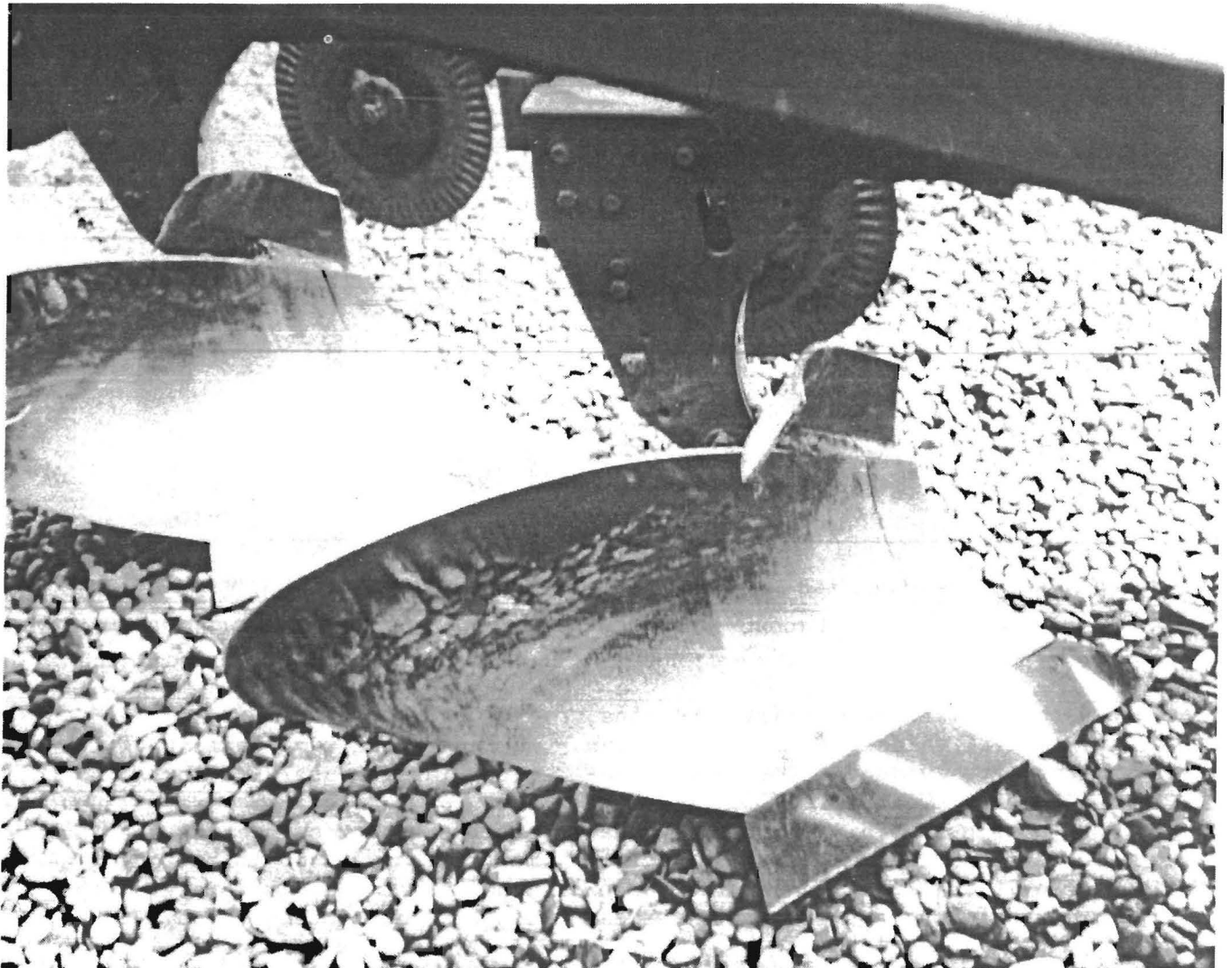


FIGURE 23. - Plowshare affixed to lower portion of one of five blade assemblies.

is tapered to a knife point to assist in cutting the soil. Wear is greatest to the share assemblies at the front and rear of the plow.

Two trials were conducted. The first involved two plowshares with commercial ferrochrome cast-on surfaces and one weld-rod hard-faced control; the second involved one experimental plowshare with a white iron alloy cast-on surface and two weld-rod hard-faced controls. Each trial involved about 140 acres. The plowshares, positions occupied on the plow, and weight losses of each share are shown in table 7.

Because the positioning on the plow partially dictates wear conditions, wear

comparisons on the basis of weight loss are difficult. While table 7 shows that weight losses for all shares on a compensated basis are nearly uniform, the appearance of the shares was not uniform. The most observable difference between the experimental shares and the control shares was that wear along the edges of the control shares was even, while wear along the edges of the experimental shares was uneven. The difference is apparent in figure 24. The uneven wear resulted from the uneven application of hard-surfacing powder to the pattern and from occasional defects at the casting-surfacing interface. The microstructure of the cast-on hard surfaces appeared

TABLE 7. - Plowshare field trial parameters and test results (140 acres plowed)

Hard surface material	Hard surface composition	Plowshare composition	Plowshare position ¹	Wt loss, lb
Commercial ferrochrome.	66.9Cr-6.4C.....	Fe-0.3C-0.4Mn-0.6Si-0.7Cr-1.7Ni-0.2Mo.	5	1.0
Do.....	...do.....	...do.....	4	1.0
Weld-rod hard surface. ²	NA.....	Fe-0.3C-0.3Si-1.2Mn..	3	.7
Do. ²	NA.....	...do.....	1	1.0
Do. ²	NA.....	...do.....	3	.8
White iron alloy	Fe-5C-21Cr-8.5Cb-9Mo-3Mn-0.3Si.	Fe-0.1C-0.6Si.....	5	1.3

NA Not available.

¹Plowshare positions run in sequence backward from the tractor.

²Control tests.

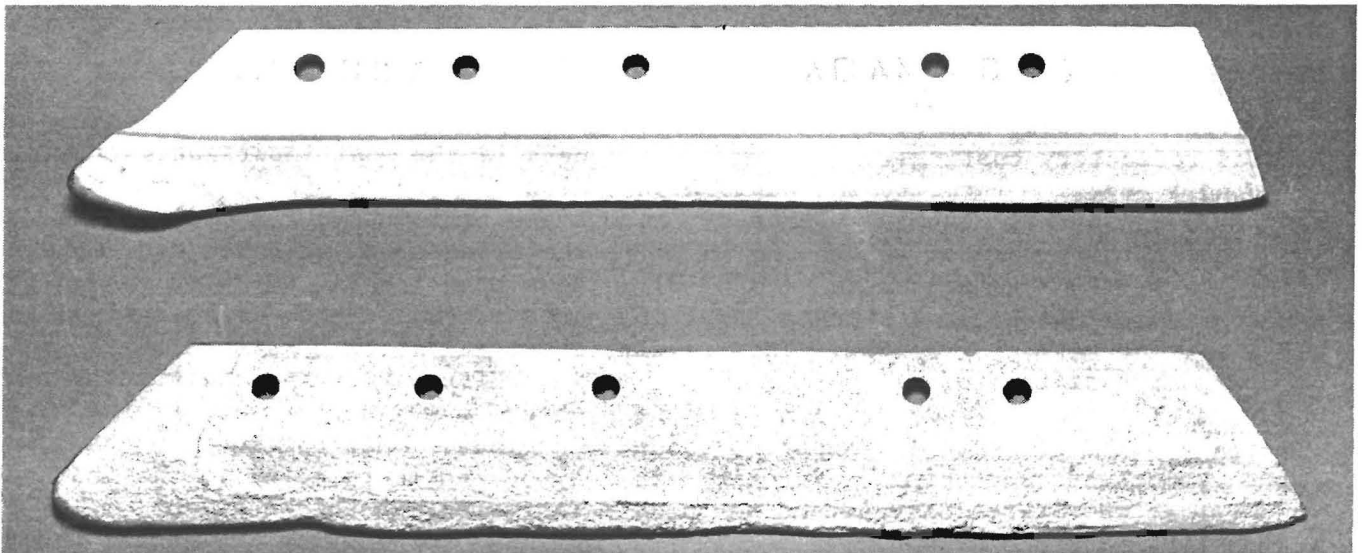


FIGURE 24. - Weld-rod hard-faced control plowshare (upper) and ferrochrome cast-on-surfaced plowshare (lower) after field trials.

similar to those observed in the bucket-wheel excavator teeth shown in figure 20. Again, thicker surfacings would have produced a greater proportion of carbides and shifted the hard-surfacing microstructure more toward the eutectic composition.

Although of prime importance, wear was not the only criteria for judging the worth of a plowshare. To be effective, a plowshare must "scour." Scouring is a process in which the flat surface of the share polishes as a result of contact with the soil. Without a polished surface, imperfections or roughness on the share causes the soil to drag across the share assembly and produce a noticeable pull on the tractor.

The farmer noted that the experimental plowshares were slow to scour. The

hand-cut polystyrene patterns produced many small imperfections, giving rise to the farmer's observation. He also noted that the tapered attachment holes were not precise, which caused the experimental shares to loosen prematurely several times. Besides the irritation involved with having to stop to tighten the loose shares, in the case of the white-iron-alloy-surfaced share, chatter produced accelerated wear along an 8- to 10-in length of the edge. Both the finish problem and the hole configuration problem could be cured if the polystyrene patterns were produced on molding machines. The positive results were that cast-on surfaces were successfully applied to thin section castings and that the cast-on surfaced shares lasted as long as the control shares.

CONCLUSIONS

Powdered hard-surfacing material can be fused in place to steel casting surfaces at the time of pouring by means of the polystyrene pattern casting process. Surfacing produced from commercial high-carbon ferrochrome powder can be formed under wide limits of binder type, binder content, powder size, pouring temperature, vacuum level, application procedure, and casting thickness. A condensed description of some of the effects of these variables is given in the following summary.

Binder type. - Cellulose and polyvinyl acetate are both acceptable binders. Polyvinyl acetate dissolves in alcohol-based refractory coatings.

Binder level. - Porosity increases with increasing binder level. Porosity is lowest at high vacuum (25 to 30 in Hg) and low pouring temperatures (1,580° C). Porosity is absent at a binder level of 0.1 pct of surfacing weight. This level is readily obtainable.

Particle size. - Powders with a fine particle size (minus 150 mesh) produce the smoothest surfacings. Porosity is lowest at an intermediate (minus 65- plus 150-mesh) particle size.

Pouring temperature. - Little effect is produced at the temperatures (1,560° to 1,610° C) investigated.

Vacuum level. - Little effect is produced on small, flat-plate sample castings. Vacuum may have a greater effect on larger castings. Porosity is lowest at high (25- to 30-in-Hg) vacuum.

Application procedure. - Little effect is produced. Porosity appears lower with a spraying and dusting procedure than with a troweling procedure.

Casting thickness. - Little effect is produced on fusion or bond quality for the thicknesses (1 to 1-3/4 in) investigated. Diffusion of surfacing into the casting is greatest with thick section castings.

Surfacing thickness. - Surfacing thickness is the most important variable. Fusion of the surfacing, dendrite formation, smoothness, and diffusion of the surfacing are greatest at thicknesses less than 1/8 in. Carbide formation, microhardness, and wear resistance are greatest at thicknesses of 1/8 to 3/16 in. Microstructures are similar to high-chromium white irons containing M_7C_3 -type carbides. Microstructure changes from hypoeutectic to eutectic as thickness is increased. A thickness of 3/16 in is maximum for casting thickness sizes in a range of 1 to 1-3/4 in.

Powder composition. - Inclusions are eliminated with high-purity ferrochrome.

Carbon additions to ferrochrome increase the carbide content of surfacings and also the wear resistance. Some white iron powder compositions have less chromium than ferrochrome, yet produce surfacings with comparable wear resistance. Exothermic compound applied over surfacings that are on thin casting sections improve surfacing fusion.

Optimum surfacings result from minus 65- plus 150-mesh powders with as little as 0.1 pct cellulose binder. Porosity levels are unaffected with pouring temperatures from 1,560° to 1,610° C, casting thicknesses from 3/4 to 1-3/4 in, and surfacing thicknesses up to 3/16 in. A possible exception is at a pouring temperature above 1,600° C and a flask pressure of less than 15 in Hg vacuum.

Surfacing thickness influences the quality of cast-on surfaces more than any other variable. Surfacing quality is optimum at a thickness of about 3/16 in for castings with section sizes between 3/4 and 1-3/4 in. At surfacing thicknesses greater than 3/16 in, shrinkage is excessive and results in an uneven surfacing contour. In addition, the outermost powder does not melt into the surfacing, and pores within the powder mixture are not filled. The unmelted powder also leaves a finish texture that is equivalent to the mesh size of the powder.

From a wear standpoint, an Fe-C-Cr eutectic microstructure is desirable. On a microscopic scale, surfacing thickness controls microstructure by providing various degrees of chill effect. Thin surfacings (up to 1/8 in thick) melt readily and completely. Solidification is slow, and diffusion of carbon from the surfacing is substantial. The microstructure is highly dendritic and is

characteristic of hypoeutectic high-chrome white cast iron. Carbides of the M_7C_3 type are precipitated interdendritically. The carbon and chromium contents of both carbides and matrices are low compared with thicker surfacings.

As surfacing thickness is increased above 1/8 in, the chill effect becomes greater, and solidification time is shortened. Diffusion is decreased, and carbide precipitation is increased. At a thickness of 3/16 in, no dendrites are apparent, and the structure represents the iron-carbon-chromium eutectic. At the eutectic, wear resistance, measured by dry-sand, rubber-wheel abrasion tests, is substantially improved. The wear resistance of cast-on ferrochrome surfacings with optimum eutectic microstructures surpasses the wear resistance of many weld-rod-applied hard facings.

The quality of cast-on surfacings made from commercial ferrochrome powders can be improved by several means. Refined ferrochromes with low impurity content reduce inclusions. More carbides are precipitated by the addition of carbon to commercial ferrochrome powders, thereby increasing wear resistance. The quality of thick surfacings and surfacings with high heat diffusivity is improved by adding exothermic material to the outside to increase melting and provide greater solidification time. Some powders with white iron compositions containing less chromium than ferrochrome are capable of producing white iron surfacings with wear resistance nearly equivalent to that of ferrochrome produced surfacings.

The potential of cast-on surfacings to replace weld-rod hard facings has been demonstrated in field tests on bucket-wheel excavator teeth and plowshares.

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APPENDIX.--RANKING GUIDE FOR DEFECTS

A minimum of three observers will make rankings from 1 to 5 for casting and surfacing defects. The observers may discuss defects but not rankings. The following guidelines will be followed to achieve consistency and to eliminate doubt.

GENERAL GUIDELINES

The general guidelines will be used when specific guidelines for specific defects are not applicable, for example, on casting defects such as sand drops, misruns, and residue cavities or on surfacing defects such as erosion, cracking, and nonfusion.

<u>Ranking</u>	<u>Extent of defect</u>
1.....	Not present.
2.....	Noticeable presence of defect but casting or surfacing is acceptable without repair.
3.....	Occurrence of defect is of sufficient severity to require minor repair.
4.....	Occurrence of defect is of sufficient severity to require extensive repair--casting is borderline between acceptable and scrap.
5.....	Occurrence of defect is too severe for repair--scrap casting.

SPECIFIC GUIDELINES

The following specific guidelines need not be rigidly adhered to if circumstances dictate otherwise. However, there should be few such situations. It should not be assumed that a defect is less important because it occurs in an area where it can do no harm and that the ranking can be more lenient because of the location of the defect. Most likely the defect could have appeared where it would be more harmful.

Guidelines for Inclusions, Gas Porosity, and Shrink Porosity

Rank according to size and/or number.

<u>Ranking</u>	<u>Extent of defect</u>
1.....	Not present.
2.....	At least one but not more than five small defects (pinhole size).
3.....	1 to 2 large ¹ and up to 5 small defects, or more than 5 but not more than 10 small defects.
4.....	More than 2 but not more than 4 large defects, and up to 10 small defects, or more than 10 but not more than 15 small defects.
5.....	Defects of sufficient size and/or number to render casting scrap.

Guidelines for Roughness

Rank according to the relative grittiness of the surfacing.

<u>Ranking</u>	<u>Extent of defect</u>
1.....	Fine.
2	
3.....	Similar to 20-grit sandpaper.
4	
5.....	Similar to 10-grit sandpaper.

¹Greater than 1/8 in diam, but not greater than 1/4 in diam. If large inclusions or holes are larger than 1/4 in diam, downgrade ranking appropriately.

Guidelines for Contour

Rank according to the overall outline of the surfacing irrespective of roughness.

<u>Ranking</u>	<u>Extent of defect</u>
1.....	Smooth.
2	
3.....	Marked by a slight dip or wave.
4	
5.....	Marked by a severe dip or wave.

Guidelines for Porosity and Inclusions
Observable in Metallography Specimens

Rank according to the number of inclusions, gas holes, or microshrink holes per X 50 frame.

<u>Ranking</u>	<u>Extent of defect</u>
1.....	None.
2.....	One per X 50 frame.
3.....	Two per X 50 frame.
4.....	Three per X 50 frame.
5.....	Four or more per X 50 frame.