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Formation and Control of Lustrous Carbon Surface Defects in Iron and Steel Castings

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ABSTRACT

This silver anniversary paper will up-date the original lustrous carbon research paper published in 1977 that described lustrous carbon defects and their formation as well as examined remedial techniques to eliminate defects in gray iron castings. This updated paper examines new phenolic urethane binder technology and compares lustrous carbon defect susceptibility to older systems. The lustrous carbon forming tendencies of 2002 phenolic urethane no-bake binders are compared to furan and ester cured phenolic no-bake binders. New methods for defect elimination include the venting and vacuum exhausting of mold gases during pouring. In addition, lustrous carbon formation in steel castings is examined and suitable methods to eliminate defect formation are discussed.

Current standard cold-box binder formulations provide virtually identical gray iron casting results compared to the 1977 research. Cold-box binder systems formulated with new, less volatile solvent systems (biodiesel or vegetable oil-based solvents) showed significantly reduced tendencies for lustrous carbon formation. Furan and ester cured phenolic no-bake binders do not produce lustrous carbon defects. Venting and application of vacuum during metal pouring were both effective in minimizing lustrous carbon wrinkling. Lustrous carbon defect formation is more likely to occur when low pouring temperatures and lengthy pouring times are used. Defects are eliminated by increasing metal pouring temperatures, pouring faster and incorporating red-iron oxide additions to sand mixes. Incorporating 2.0 percent red-iron oxide in the sand mixes also eliminates lustrous carbon defects in steel castings.

INTRODUCTION

HISTORICAL BACKGROUND: The growth in both phenolic urethane cold-box and no-bake binders since 1970 has been phenomenal and is shown in Figure 1.

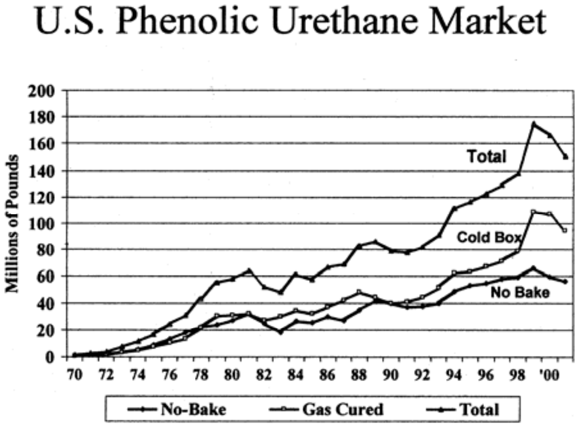


Figure 1: Growth of phenolic urethane binders in the United States

In early 1971, during the time of the initial lustrous carbon research, only 2.7 million pounds of cold-box and no-bake phenolic urethanes were consumed by the U.S. foundry industry. When the original lustrous carbon paper was published in

1977, shipments of both cold-box and no-bake phenolic urethanes had grown to 31.0 million pounds - an astounding figure at the time. During the first year of this millennium, 150 million pounds of both resins were consumed in the United States. Estimated worldwide use is generally considered to be over 300 million pounds.

Shortly after the introduction of cold-box phenolic urethane binders, casting defects, generally described as severely wrinkled surfaces defects, were reported by some of the early users of these binders. A few foundries also reported "leakers" in pressure-tight castings. The technical literature of the time contained little information regarding the specific conditions that increased the likelihood of these defects, soon to be known as “lustrous carbon”, or methods to eliminate these defects. The available information suggested that defect formation is affected by pouring time and gating system design. Slow, turbulent filling and low pouring temperatures were reported to aggravate defect formation. (Clifford, M.J.).

Lustrous carbon surface imperfections were often referred to as "resin"; "kish" and "soot" defects, as the name "lustrous carbon" wasn't commonly used to describe these defects. The defects almost always occurred when using binders that evolved large quantities of carbonaceous decomposition products during the filling of the mold by molten metal. Such carbonaceous residues, however, can be beneficial when present in lesser amounts, as they provide a reducing atmosphere that minimizes oxidation at the mold-metal interface and generally improves casting surface finish and peel. In steel castings, particularly those with thick sections, pockmarking may appear on casting surfaces. In high-alloy steels, such as stainless steel and nickel-base alloys, appreciable amounts of surface porosity and carbon pickup might occur; both are undesirable. Lustrous carbon defects have also become one of the major problems in lost foam castings. (Moll, N.)

Lustrous carbon defects usually appear on castings as areas containing wrinkled, shiny surfaces, which often resemble cold shuts or seams. The appearance of these wrinkled or lapped areas has often been compared to that of elephant skin, alligator skin or crows feet. Usually the defects occur on external surfaces but can also form on cored surfaces of hydraulic cylinders, boiler sections and pumps. In thin casting sections, lustrous carbon accumulations and entrapment can result in hydraulic unsoundness as well as sub-surface "cold shut" defects. Thick metal sections have been reported to be less prone to lustrous carbon defects than thin sections. Under certain conditions, lustrous carbon defects may result in sub-surface blistering or surface laminations. Typical lustrous carbon defects found in a few gray iron industrial castings are illustrated in Figure 2.

a: Wrinkles on automotive brake caliper ***b: Blister on disc brake rotor*** ***c: Surface lamination on disc brake***

d: Surface wrinkles on pully hub ***e: Surface wrinkles in oil pan which leaked*** ***f: Surface wrinkling on lost foam truck transmission part***

Figure 2: Examples of typical lustrous carbon defects in industrial castings.

Microstructural examination of areas containing these defects often reveals discontinuities extending deep into the casting body. Figure 3 illustrates typical lustrous carbon surface pockmarking defects found in heavy section steel castings.

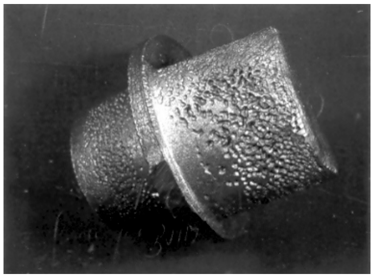


Figure 3: Surface pockmarking on steel casting

Lustrous carbon defects can occur with many binder systems. The defects can form with oil-alkyd-isocyanate no-bake binders, cold-box and no-bake phenolic urethane binder systems, certain grades of furfuryl alcohol, urea-furfuryl alcohol (furan) no-bake binders and phenolic shell-sand systems (Wragg, Greenhill, Clifford, Behring). Lustrous carbon related surface defects are not peculiar to the chemically curing binder systems; they also are commonly found on castings made in green sand molds containing large amounts of seacoal (Kvasha, Bindernagel, Petrela, Beale, Draper).

BINDER DEVELOPMENTS 1977 to 2002 The phenolic urethane binder system consists of no-bake and gas cured resins. Part 1 is a phenolic resin (poly-benzylic-ether-phenolic resin) diluted approximately 50 percent with solvents. Part 2 is a polymeric di-isocyanate resin diluted with approximately 25 percent solvents. The solvents can be composed of aliphatic, aromatic or vegetable oil-based derivatives (Biodiesel), or various blends thereof. One of the primary purposes of the solvents is to reduce binder viscosity. Typically, the viscosities of the Part I and Part II resins are adjusted to 300 cps or lower to provide good pumping properties, rapid and efficient sand coating qualities and good flowability of mixed sand. Secondly, the solvents enhance resin reactivity and control bench life. An amine-based catalyst is used as the curing agent for the no-bake binder while a gaseous amine (triethylamine or dimethylethyl amine) is used for the gas-cured binder.

Although the general chemistry of phenolic urethane binders remains essentially the same as the system investigated in 1977, (Naro 1977) there have been numerous modifications in resin formulations involving both the phenolic base resin as well as the solvent system package. The Part I phenolic base resin has been modified to reduce odor by reducing free formaldehyde levels. This is especially apparent when hot foundry sands are used. In addition, because of efforts to reduce solvent evaporation, the solvent system has been modified to incorporate higher boiling point solvents or new solvents systems with improved environmental properties (Biodiesel). Because these solvents remain entrapped in the binder film, the newer formulated binder systems might, in fact, be more prone to lustrous carbon surface defects.

All current organic binder systems are based on the elements carbon, hydrogen, oxygen, and in some cases nitrogen. The chemical makeup of phenolic urethane cold-box and no-bake binders, compared to other popular binder systems is shown in Table 1 (Chang).

Table 1: Approximate chemical composition of cold-box and no-bake binders (Chang)

Binder Type	% Carbon	% Hydrogen	% Nitrogen	% Oxygen
PU Cold-box (1971)	72.0	8.5	3.9	15.5
PU No-bake (1971)	72.0	8.5	3.9	15.5
PU Cold-box (2002 standard)	73.0	7.9	3.9	14.8
PU Cold-box (2002 biodiesel)	68.4	8.1	4.0	20.0
(Biodiesel or vegetable-oil based solvents)				
PU Cold-box (2002 all aromatic)	74.6	7.6	3.4	14.8
(All aromatic solvents)				
PU No-bake (2002 standard)	75.3	8.0	3.4	13.7
Premium Furan No-bake (2002)	52.9	6.6	0.56	38.4
Phenolic Ester No-bake (2002)	31.5	8.4	0.02	60.1

At ferrous casting temperatures, the presence of these elements and their subsequent decomposition can produce a variety of casting defects. The following gaseous reactions are thermodynamically possible, and under the right conditions, might occur at the mold-metal interface (Naro 1999):

Binder ----------- > H (nascent) -> H_2 (g)
Binder ----------- > N (nascent) ---> N_2 (g)
Fe + H_2O vapor (binder) --------> FeO + 2H (nascent)
3 H_2 (binder) + N_2 (binder) > $2NH_3$(g) --------> 6H(nascent) + 2N(nascent)
FeO + C (binder) ---------> CO (g) + Fe

Although the first four reactions are likely to promote both surface and subsurface porosity defects, the last reaction usually results only in surface defects, such as surface pockmarking or, more frequently, lustrous carbon laps and surface wrinkles (Naro 1977).

Clearly, many factors are involved in the development of binder-associated defects. This paper will investigate, using the same tests developed in the early 1970s, how susceptible new binder formulations are to lustrous carbon formation.
This updated paper will also review old and new methods to eliminate lustrous carbon defects in both gray irons as well as steels.

Experimental Procedure

In updating this paper, the world's leading binder manufacturer made available its foundry testing facility for pouring new test castings with current binder formulations. The accompanying experimental procedure will review the original materials and procedure as well as those used to evaluate the new binder systems.

The experimental program used in this investigation was divided into three phases:

1. the development of a suitable test casting configuration with the capability to produce lustrous carbon defects;
2. the delineation of core-making and metal-processing variables that have an effect on lustrous carbon defects; and
3. the evaluation of current binder systems compared to the systems tested 25 years ago.

TEST CASTING DESIGN

Gray Iron - The test casting illustrated in Figure 4 was selected for studying lustrous carbon formation in iron castings. The plate test casting provides a large surface area-to-volume ratio that is exposed to radiant heating during the filling process. Also, the configuration provides a large surface for examination of defects and, therefore, information regarding the effects of metal flow patterns. No provisions were made for risering the test piece since only surface studies were to be made. The gating system consisted of a tapered sprue, a horseshoe-type gating system and four ingates. By changing the choke diameter of the sprue, the time required to fill the mold could easily be varied.

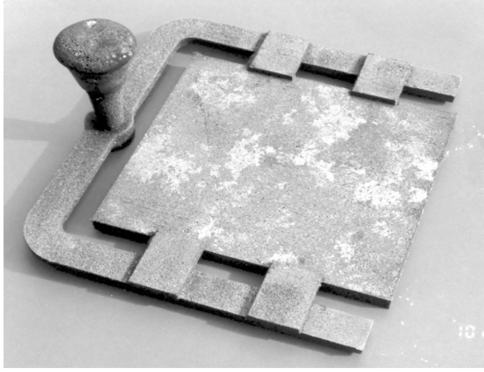


Figure 4: Configuration of lustrous carbon test casting, 9 inches long by 8 inches wide by ½ in thick, sprue choke – ½ inches

Steel - To simulate heavy section castings, the Steel Founders' Society "scab block" test casting was used. The casting is roughly 6 inches wide, 6 inches long and 5 inches high. This design was selected because it was one of the larger test castings that could be conveniently poured in an experimental foundry. Thin section castings used the same test plate illustrated in Figure 4.

MOLDING MATERIALS AND ADDITIVES

The base sand mix used for most of the testing consisted of Michigan lake sand. The AFS screen distributions of the lake sand and the other molding aggregates that were investigated are shown in Table 2. The bulk of the original experimental work was conducted using the no-bake version of the phenolic urethane binder although studies also were conducted with the gas-cured version or cold-box binder to establish relative performance characteristics.

Table 2: Sands and AFS GFN distribution

Sand Type	#20	#30	#40	#50	#70	#100	#140	#200	#270	Pan	AFS GFN
Michigan lake sand	--	--	3.1	22.5	41.7	24.0	7.4	0.7	--	--	56
W/D Silica sand 1	2.2	38.6	57.6	1.4	0.2	--	--	--	--	--	26
W/D Silica sand 2	--	--	4.6	18.4	29.6	28.6	14.9	3.0	0.5	0.2	67
W/D Silica sand 3	--	--	--	0.4	8.2	46.6	23.2	15.4	4.2	2.0	95
Crushed sandstone	--	18.2	57.7	20.0	2.8	1.0	0.2	--	--	--	61
*W/D – washed and dried											

This updated paper investigated current phenolic urethane cold-box binder formulations, phenolic urethane no-bake binders, a nitrogen free furan no-bake binder and an ester cured no-bake phenolic binder system. The various binder systems investigated are shown in Table 3.

Table 3: Binders evaluated for lustrous carbon susceptibility

Binder	Percentage / Ratio (Pt 1 to Pt 2)	Comments
Cold-box A	1.5% BOS, 55/45 ratio	1971 formulation
Cold-box B	1.5% BOS, 55/45 ratio	2002 standard formulation, long bench-life solvents (5% biodiesel)
Cold-box C	1.5% BOS, 55/45 ratio	2002 formulation, long bench-life solvents (all biodiesel), an environmentally friendly system
Cold-box D	1.5% BOS, 55/45 ratio	Experimental system incorporating all aromatic, low boiling point, high evaporation rate solvents
PU No-bake A	1.5% BOS, 55/45 ratio	1971 formulation
PU No-bake B	1.5% BOS, 55/45 ratio	2002 standard formulation, low odor, low free formaldehyde, high solids content, minimal aromatic solvent content
Furan No-bake	1.5% BOS, 30% catalyst, BOB	Premium, nitrogen free furan no-bake binder
Phenolic-Ester No-bake	1.5% BOS, 30% co-reactant, BOB	Ester cured phenolic no-bake binder
*BOS – Based on sand weight, BOB – Based on binder weight		

All sand mixes were prepared in a small batch mixer by adding the phenolic resin component (Part 1) and catalyst to the sand and then mixing for 2 minutes. Next, the appropriate amount of polymeric isocyanate (Part 2) was added and mixed for an additional 2 minutes. The prepared mix was immediately hand-tucked into the test patterns. Strip times averaged 5 minutes. Cold-box mixes were cured with triethylamine. Molds were aged overnight before pouring. The furan no-bake and the ester cured phenolic no-bake binders were prepared in a similar manner; catalyst or co-reactant was first added to sand, mixed for 2 minutes, then the resin was added and mixed for an additional 2 minutes before being discharged into the test pattern.

The selection of suitable sand additives was determined after reviewing thermodynamic data (Elliot). Because a reducing atmosphere within the mold cavity appears to promote lustrous carbon formation, sand additives were selected to minimize or change the mold atmosphere to one promoting oxidizing conditions. The materials selected included carbonates, nitrates, borates, sulfates and several metal oxides, each of which is capable of providing an oxidizing atmosphere under equilibrium conditions at the pouring temperatures employed. All of the materials used were of technical grade or higher purity and in powder form, 200 mesh or finer.

PREPARATION OF TEST CASTINGS

Gray iron test castings were poured with a high carbon-equivalent, inoculated Class 30 iron. Melts were superheated to 2800°F (1538°C) in a 300 pound, basic-lined induction furnace and tapped into preheated, clay-graphite crucibles. Pouring temperatures were carefully monitored through measurements in the ladle with an immersion pyrometer. All test castings were poured at 2500°F (1371°C) except in those cases where the effect of varying metal temperature was determined. The time needed to completely fill the test mold was recorded for each casting. Most castings were poured in 25 seconds except when pouring time effects were determined. Castings were allowed to cool overnight and were shaken out the next day.

Steel castings were prepared in the same manner as described above. A nominal 8620 steel was used for these evaluations. Plain carbon steel punchings were melted in an induction furnace, followed by an induced carbon boil for refining. Then the heat was blocked with silicon and manganese. Next, the necessary ferroalloys and nickel were added and induction stirred. Lastly, the heat was tapped into preheated ladles and deoxidized with the addition of 0.10 weight percent aluminum shot.

MACRO AND MICROSTRUCTURAL EXAMINATION

Each casting was carefully examined upon shakeout and the general conditions of the cope, drag and side surfaces, shakeout behavior and extent of lustrous carbon surface deposits and wrinkling extent were recorded. Selected test castings exhibiting typical lustrous carbon defects were photographed at 1.5-power magnification. Other castings exhibiting severe defects were sectioned and metallographically examined. A surface defect rating system was developed to assess relative lustrous carbon forming tendencies. The following rating system was used to assess relative surface finish of the test castings:

1 - Excellent, no evidence of lustrous carbon (LC) films at shakeout, dull finish
2 - Good, nil amounts of LC films at shakeout, general dull finish
3 - Fair, some shiny deposits of LC films, some surface wrinkling
4 - Poor, shiny deposits of LC films adhering to casting surfaces, moderate surface wrinkling
5 - Very poor, heavy deposits LC films adhering to the casting at shakeout, severe wrinkling

RESULTS AND DISCUSSION

GRAY IRON - EFFECT OF POURING TEMPERATURE

Results of tests to determine the effect of varying pouring temperatures on lustrous carbon formation are listed in Table 4.

Table 4: Effect of pouring temperature on lustrous carbon formation

Pouring Temperature	Presence of lustrous carbon films	Surface appearance – extent of wrinkling
2700^{O}F	None	1 – excellent – no wrinkling
2620^{O}F	Yes – minor amounts	3 – fair – minor wrinkling
2575^{O}F	Yes – minor amounts	3 – fair – minor wrinkling
2545^{O}F	Yes – moderate amounts	4 – poor – moderate wrinkling
2500^{O}F	Yes – moderate amounts	4 – poor – moderate wrinkling
2470^{O}F	Yes – large amounts	5 – very poor – severe wrinkling
2410^{O}F	Yes – large amounts	5 – very poor – severe wrinkling
2350^{O}F	Yes – large amounts	3 – fair, minor wrinkling, sluggish metal flow pushed films to far edge of casting
2250^{O}F	Yes – large amounts	3 – fair, minor wrinkling, sluggish metal flow pushed films to far edge of casting
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring time – 25 seconds		

Lustrous carbon deposits and surface defects were not present on castings poured at temperatures of 2700°F (1482°C) or higher. Decreasing the pouring temperature produced increasing amounts of shiny sheets of carbonaceous films and deposits that adhered to the castings during shakeout. These surfaces contained numerous areas of wrinkling that increased both in extent and severity with decreasing pouring temperature. Examples of shiny, sooty lustrous carbon films, found clinging to casting surfaces, are illustrated in Figure 5.

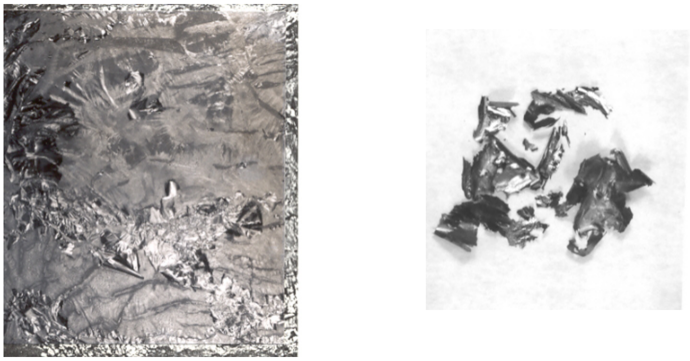


Figure 5: Examples of lustrous carbon films adhering to test casting at shakeout

Other typical surface wrinkling defects found on the test castings are shown in Figure 6.

Figure 6: Surface of test casting containing typical wrinkling defects

On an absolute basis, although the degree of surface wrinkling for any given casting temperature was not always consistent, deposits of shiny, silvery-black carbon were always present when low pouring temperatures were used in the casting tests.

Pouring temperatures of 2350°F (1288°C) and lower produced mis-run castings. The extent and severity of surface wrinkling was reduced on a major portion of the casting surfaces. However, the casting surfaces became severely wrinkled as solidification proceeded against the accumulation of lustrous carbon films at the end of the mis-run test castings (see Figure 7). Although the extent and severity of surface wrinkling was reduced on an absolute basis, casting surfaces, which filled last, became severely wrinkled as final solidification proceeded against accumulations of dislodged lustrous carbon films.

Figure 7: Severe surface wrinkling resulting from solidification against accumulations of lustrous carbon

The reduced metal fluidity at the lower temperatures apparently allowed most of the films to be pushed along ahead of the advancing metal stream and to accumulate at the furthest position from the down sprue. Copious amounts of lustrous carbon films were readily apparent when the test molds were opened for casting shakeout.

The elimination of lustrous carbon by using high pouring temperatures can probably be attributed to several reactions occurring at the mold-metal interface. High pouring temperature increases both the amount and rate of formation of an iron-oxide skin during pouring. Because the reaction rate between carbonaceous films from binder decomposition and iron oxide surface films becomes greater with increasing temperature, the combined effect of both factors appears to result in the oxidation of carbonaceous by-products. At higher pouring temperatures, traces of minute surface pockmarks from carbon monoxide reactions were apparent. Also, lustrous carbon films generated from the binder tend to dissolve much more readily at the higher pouring temperatures.

EFFECT OF POURING TIME

To determine the effect of pouring time on defect formation, pouring times were varied from 15 to 39 seconds by modifying the sprue choke area. Castings were poured at 2500°F (1371°C), a temperature that previously was shown to induce lustrous carbon defect formation. The test results are listed in Table 5.

Table 5: Effect of pouring time on lustrous carbon formation

Pouring time	Presence of lustrous carbon films	Surface appearance – extent of wrinkling
39 seconds	Yes – large amounts	5 – very poor – severe surface wrinkling
23 seconds	Yes – large amounts	4 – poor, moderate wrinkling
17 seconds)	Yes – trace amounts	2.5 – fair, trace wrinkling
15 seconds	Yes – trace amounts	2 – fair to good, trace wrinkling
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F		

Castings with long pouring times exhibited severe cold shutting with considerable amounts of shiny, lustrous carbon films clinging to the casting surface after shakeout. Lustrous carbon defects were minimized when the choke area was enlarged and the pouring time was shortened. Although traces of lustrous carbon defects or wrinkling still were evident, rapid filling or flooding the mold cavity tended to substantially minimize the amount of carbonaceous films. Apparently, fewer films were in contact with the molten streams during pouring and also at final solidification.

EFFECT OF BINDER LEVEL

Table 6 lists the results obtained using various binder levels on lustrous carbon formation. For these tests, the binder level for the base sand mix was varied from 0.75 percent to 2.0 percent. Because cores and molds with binder levels less than 0.75 percent usually have reduced strengths and scratch hardness, further binder reductions were not investigated. Regardless of binder level used, shiny films of lustrous carbon adhered to the test castings at shakeout when test pieces were poured at 2500°F (1371°C). Test casting surfaces all contained trace wrinkling.

Table 6: Effect of phenolic urethane binder level on lustrous carbon susceptibility (2500^{O}F)

Binder level	Presence of lustrous carbon films	Surface appearance – extent of wrinkling
0.75% BOS	Yes – moderate amounts	4 – poor – moderate wrinkling
1.0% BOS	Yes – moderate amounts	4 – poor – moderate wrinkling
1.5% BOS	Yes – moderate amounts	4 – poor – moderate wrinkling
2.0% BOS	Yes – moderate amounts	4 – poor – moderate wrinkling
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds		

Table 7 lists the results of a similar study on binder level but with the pouring temperature increased to 2700°F (1482°C).

Table 7: Effect of phenolic urethane binder level on lustrous carbon susceptibility (2700^{O}F)

Binder level	Presence of lustrous carbon films	Surface appearance – extent of wrinkling
0.75% BOS	None present	1.5 – Good, no wrinkling
1.0% BOS	None present	1.5 – Good, no wrinkling
1.5% BOS	None present	1.5 – Good, no wrinkling
2.0% BOS	None present	1.5 – Good, no wrinkling
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2700^{O}F, pouring time – 25 seconds		

Test casting appearance at shakeout was excellent and carbonaceous films were absent, as were wrinkle defects on the casting surfaces. Test castings made using extreme binder levels of 3.0 percent were also defect free. This further illustrates the importance of employing high pouring temperatures for lustrous carbon elimination. If pouring temperatures of 2700°F (1482°C) or higher cannot be used because of equipment limitations or casting specifications, other methods to reduce the amount or rate of binder decomposition must be employed to eliminate lustrous carbon. In evaluating the lustrous carbon tendencies of phenolic urethane cold-box binders, using the same conditions shown in Tables 6 and 7, casting performance was almost identical to the phenolic urethane no-bake binders.

EFFECT OF PHENOLIC URETHANE BINDER RATIO

Since the Part 1 phenolic resin has a slightly higher carbon content than does the Part 2 polymeric isocyanate, the ratio of Part 1 to Part 2 was varied to investigate the effect of binder ratio on lustrous carbon formation. Molds with Part 1 to Part 2 ratios of 70/30, 60/40, 50/50, 40/60 and 30/70 were prepared at 1.5 percent total binder and were poured at 2500°F (1371°C).

Molds prepared with ratios of 70/30, 60/40, and 50/50 had high tensile strengths and high scratch hardness. Ratios of 40/60 and 30/70 produced lower strength molds. Lustrous carbon films were observed adhering to the casting surfaces at shakeout regardless of the binder ratio used. Castings produced with binder ratios of 70/30, 60/40, and 50/50 provided similar performance with some traces of surface wrinkling. Minor levels of lustrous carbon wrinkling occurred at 40/60 ratios along with some surface burn-in. Binder ratios of 30/70 produced very poor casting surface finish and extensive lustrous carbon wrinkling defects formed on drag surfaces. Unbalanced ratios favoring excess Part 2 contain un-reacted polymeric isocyanate. This condition appears to increase the amount of lustrous carbon surface wrinkling propensity. Binder ratios favoring excess polymeric isocyanate levels also had higher total carbon concentrations for the same solvent system. The reduced solvent or higher solids content of Part 2 resins was responsible for the increased levels of lustrous carbon.

EFFECT OF SAND TYPE ON LUSTROUS CARBON FORMATION

Table 8 lists the effect of sand type on lustrous carbon defect formation.

Table 8: Effect of sand type on lustrous carbon formation

Sand type	Presence of lustrous carbon films	Surface appearance – extent of wrinkling
Michigan Lake	Yes – moderate amounts	4 – poor – moderate wrinkling
W/D Silica 1	Yes – minor amounts	4 – poor – trace wrinkling
W/D Silica 2	Yes – minor amounts	3 – fair – trace wrinkling
W/D Silica 3	Yes – minor amounts	3 – fair – trace wrinkling
Crushed sandstone	Yes – moderate amounts	4 – poor – moderate wrinkling
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds		

Castings poured at 2500°F (1371°C) or below in the Michigan lake sand contained continuous films of lustrous carbon adhering to the casting surfaces upon shakeout. Lustrous carbon wrinkling defects were present on both the cope and drag surfaces of the casting. Use of round-grained washed silica sand with a grain fineness (AFS GFN) of 67 minimized the formation of lustrous carbon wrinkling defects. Although lustrous carbon was still generated by binder decomposition, it tended to adhere very tenaciously as a “filmy skin” to the sand surface. An easily detachable skin of sand bonded with a continuous film of lustrous carbon was found on these test castings during shakeout (see Figure 8). The formation of this “filmy lustrous carbon skin”, prevented lustrous carbon films from being flushed along by the flow of molten iron and inhibited the formation of wrinkling defects in the solidifying metal surface.

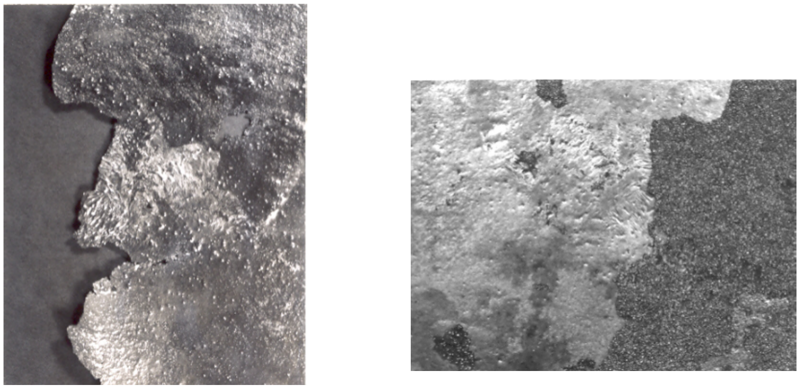


Figure 8: Layer of lustrous carbon bonded sand (left) and cast surface from which bonded layer was removed (right)

The effect of grain size was investigated using washed silica sands of different AFS grain fineness numbers. A fine silica sand (AFS GFN 95) produced results similar to the AFS GFN 67 silica sand. The lustrous carbon films that formed adhered to the sand, and minimal wrinkling defects were observed on the casting. The coarser silica sand (AFS GFN 26) exhibited extensive surface penetration. Lustrous carbon sheets also were present in the penetrated layer, but again, few wrinkling defects were observed. A coarse crushed sandstone-type sand (AFS GFN 42) produced results similar to those of the Michigan lake sand.

These results indicate that sand grain size has little effect on the formation of lustrous carbon defects, however, sand grain geometry seems to have an effect on reducing lustrous carbon wrinkling. Lustrous carbon films seemed to preferentially form a continuous and tightly bonded film with round grained sands; the lustrous carbon films remained at the mold-metal interface and were not dislodged by molten metal flow.

EFFECT OF 2002 BINDER FORMULATIONS

Phenolic Urethane Cold-box Binders – Although the base phenolic resin used in cold-box binders has remained essentially the same since the mid-1970s, significant changes and modifications have been made in the area of solvents. Solvent modifications have been incorporated into cold-box binders to increase bench-life of mixed sand, to reduce odor, to improve cured sand properties, and more recently, to provide binder systems that are more environmentally friendly and eliminate or minimize evaporation. Using those conditions that promoted lustrous carbon formation, numerous tests were run to compare lustrous carbon forming tendencies of new systems compared to mid-1970 cold-box binder formulations. The older cold-box binders were formulated using original recipes and solvents from the 1970s..

Table 9 lists the results of casting tests comparing old versus new resin formulations.

Table 9: Effect of cold-box binder solvent formulation on lustrous carbon susceptibility

Binder system (solvent package)	**Presence of lustrous carbon films**	**Surface appearance – extent of wrinkling**
PU CB (1971 formulation)	Yes – moderate deposits	4 – poor – moderate wrinkling
PU CB (2002 std. formulation)	Yes – heavy deposits	5 – very poor, minor wrinkling
PU CB (2002 all Biodiesel)	None (dull surface)	2.0 – fair to good, no wrinkling
PU CB (2002 all aromatic)	Yes – trace amounts	3.5 – fair to poor, minor wrinkling
Test conditions: 1.5% Phenolic urethane cold-box binder on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds		

The year 2002 phenolic urethane cold-box binder provided slightly worse lustrous carbon generating susceptibility compared with early 1970 versions of the binder. Somewhat greater quantities of lustrous carbon films adhered to the casting at shakeout. Surface wrinkling was identical. Cold-box binders formulated with all biodiesel solvents showed superior casting performance. It was interesting to note that the all biodiesel solvent based cold-box binder had a dull surface, and lustrous carbon films were totally absent. Cold-box resins based on biodiesel solvents contained only 68 percent carbon compared with 72 percent carbon for the 1970s formulation and 73 percent for the standard 2002 system. The oxygen level of the biodiesel-based resin was almost 5 percent higher than standard cold-box formulations. This combination of reduced carbon level and increased oxygen content was obviously responsible for the elimination of lustrous carbon.

Incorporating all aromatic solvents into a phenolic urethane cold-box binder tended to minimize, but not eliminate, lustrous carbon film formation. Although aromatic solvents are high in carbon, these low boiling point solvents evaporate prior to casting and provided reduced levels of lustrous carbon. During prolonged core storage, it is anticipated that a significant portion of the low boiling point solvents will evaporate resulting in reduced lustrous carbon tendency. During casting, low boiling point solvents will "flash off" rapidly compared to high boiling point solvents, which have a greater tendency to condense and form lustrous carbon at the mold metal interface.

Although the 1977 lustrous carbon research downplayed the effect of solvents on lustrous carbon formation, clearly solvents do effect lustrous carbon formation. The newly reformulated biodiesel solvents, with reduced carbon and increased oxygen levels, provide vastly improved resistance to lustrous carbon defects.

No-bake Binders – The lustrous carbon susceptibilities of year 2002 phenolic urethane no-bake binders compared with early 1970 versions of the binder are shown in Table 10. Also shown in Table 10 are the casting performance of a premium grade furan no-bake binder and an ester cured phenolic no-bake binder.

Table 10: Effect of no-bake binder type and formulation on lustrous carbon susceptibility

Binder system (solvent package)	**Presence of lustrous carbon films**	**Surface appearance – extent of wrinkling**
PU NB A (1971 formulation)	Yes – heavy deposits	4 – poor – moderate wrinkling
PU NB B (2002 std. formulation)	Yes – moderate deposits	3 – fair, minor wrinkling
Furan no-bake binder	None	1.5 – very good, no surface wrinkling
Phenolic Ester no-bake	None	1.0 – excellent, no wrinkling
Test conditions: 1.5% Phenolic urethane no-bake binder on Michigan lake sand (BOS) 1.5% Phenolic ester (BOS), 1.5% Furan, 30% catalyst Pouring temperature – 2500^{O}F, pouring time – 25 seconds		

The year 2002 version of the phenolic urethane no-bake binder provided improved casting performance and reduced levels of lustrous carbon formation compared with the binder formulated with 1970s solvents and base resins. In fact, the incoming metal flow patterns could easily be detected on test-casting surfaces, which contained heavy, shiny lustrous carbon deposits. Neither the premium furan no-bake binder nor the phenolic ester cured no-bake binder showed any evidence of lustrous carbon formation. Although both as-cast surfaces after shakeout were dull, the phenolic ester no-bake produced the best as-cast surface of all the binders tested.

ELIMINATION OF LUSTROUS CARBON DEFECTS

Effect of Sand Additives - Numerous compounds were evaluated as additives to change the reducing atmosphere in the mold cavity to an oxidizing atmosphere at low pouring temperatures. Materials were selected after careful study of thermodynamic data. They included metal oxides, sulfates, borates, carbonates and nitrates.

Table 11 summarizes results obtained with the better performing sand additions.

Table 11: Effect of sand additives on lustrous carbon formation

% Additive	**Presence of lustrous Carbon films**	**Surface appearance – extent of Wrinkling**	**Comments**
2% Fe_3O_4 (black)	None	5 – traces of surface wrinkling	Severe surface deterioration
2% Fe_2O_3 (red)	None	1.5 – good, no wrinkling	Minor surface finish deterioration
2% $Fe_2O_3 \cdot nH_2O$ (yellow ochre)	None	1.5 – good , no wrinkling	Minor surface finish deterioration
1% $Al_2(SO_4)_3$	None	2 – traces of surface wrinkling	Dull, oxidized surface
1% MnO_2	Yes – heavy deposits	5 – severe surface wrinkling	Minor surface finish deterioration
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds			

Hematite (red iron oxide Fe_20_3) and yellow ochre were the only additives that completely eliminated lustrous carbon film formation and surface wrinkling. However, a 2.0 percent addition level was required for complete elimination of lustrous carbon films and surface defects. Magnetite, which contains only a few weight percent less oxygen than hematite, was not as effective in eliminating lustrous carbon when used in either powdered (200 mesh) or coarser forms. All of the metal oxides tested produced varying degrees of deterioration in the casting surface. Although effective in oxidizing lustrous carbon, the enhanced oxidizing conditions created by these additives appears to promote fayalite or burn-on reactions at the mold-metal interface.

Although additions of iron or sodium sulfates reduced the severity of lustrous carbon formation, use of aluminum sulfate was more effective. Other compounds were ineffective in reducing lustrous carbon formation or produced localized fluxing and severe surface deterioration.

Incorporation of oxidizing additions to sand mixes is not without disadvantages. Table 12 summarizes the effects of additives on tensile strength properties of sand mixes.

Table 12: Effect of oxidizing additives on core tensile strength

% Additive	**24 hour tensile strength**
None	350 psi
1.0% Fe_2O_3 (red)	302 psi
1.5% Fe_2O_3 (red)	278 psi
2.0% Fe_2O_3 (red)	252 psi
2.0% $Fe_2O_3 \cdot nH_2O$	162 psi
1.0% $Al_2(SO_4)_3$	268 psi
W/D silica sand with 1.5% phenolic urethane no-bake binder	

Additions of red iron oxide up to 1.5 percent resulted in only a minor decrease in tensile strength but the larger additions of 2.0 percent produced a moderate 70 pounds to 80 pounds per square inch (psi) decrease in strength. Yellow ochre performed similarly. Aluminum sulfate additions at the 1 percent level produced little or no change in tensile properties. Larger additions were not investigated because of their adverse effect of strength reductions at a given binder level.

Effect of Venting - To study the effect of extracting carbon-rich gases from the mold cavity during pouring operations, a series of test castings were poured in which both venting and application of a positive vacuum were applied to test molds. The results of the venting studies are shown in Table 13.

Table 13: Effect of venting and exhausting on lustrous carbon formation

	Presence of lustrous carbon films	**Surface appearance – extent of Wrinkling**
Standard – no venting	Yes – heavy deposits	4 – poor – moderate wrinkling
30 – 0.35 in. diameter vents	Yes – moderate deposits	4 – poor, minor wrinkling
Vacuum assisted venting	Yes – moderate deposits	2.5 – fair to good, no surface wrinkling
Vacuum supplied from “shop vacuum” pulling through 1.1 inch diameter vent (1.3 square inches)		
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) 2002 binder versions, pouring temperature – 2500^{O}F, pouring time – 25 seconds		

In non-vented molds, relatively heavy deposits of lustrous carbon adhered to the test casting at shakeout. General surface finish also was very poor, though only minor surface wrinkling was observed. Venting of test molds by drilling 30 vents, each with a diameter of 0.35 inches, reduced the amount of lustrous carbon deposits on test castings. General surface finish improved only marginally, and minor evidence of surface wrinkling was still apparent. Using a vacuum to assist in removing carbon laden decomposition products from the mold cavity improved the surface finish somewhat, though test castings still showed a very shiny, silvery surface with moderate deposits of lustrous carbon.

Effect of Mold Coatings - The use of mold coatings was investigated to determine their effect on the formation of lustrous carbon defects. Two coats of an alumina wash were applied to the sprue, gating, and plate surfaces of test molds. The wash was air-dried for 24 hours. Lustrous carbon films adhered to the casting upon shakeout, and several wrinkling defects were found on the cope surface.

A number of coatings were formulated to promote oxidizing conditions at the mold-metal interface in an attempt to minimize lustrous carbon formation. Table 14 summarizes the results obtained with oxidizing coatings.

Table 14: Effect of oxidizing mold coatings on lustrous carbon formation

Mold coating	Presence of lustrous carbon films	Surface appearance – extent of Wrinkling	Comments
Alumina (2 coats)	Moderate amounts adhering to casting	3 – fair, traces of surface wrinkling	Moderate amounts adhering to casting
Manganese Dioxide (2 coats)	Moderate amounts adhering to casting	3.5 – fair, traces of surface wrinkling	Severe surface finish deterioration
Zinc Oxide (2 coats)	Moderate amounts adhering to casting	3.5 – fair, traces of surface wrinkling	Moderate surface finish deterioration
Yellow Ochre (2 coats)	Trace amounts adhering to casting	3 – traces of surface wrinkling	Moderate amounts adhering to casting
Test conditions: 1.5% Phenolic urethane no-bake binder, 55/45 ratio, on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds			

Manganese dioxide, zinc oxide and yellow ochre coatings did not eliminate lustrous carbon defects and resulted in deterioration of the casting surface finish. Burn-on was particularly heavy with the manganese dioxide wash. Apparently, hydrocarbon gases and residues generated from binder decomposition during pouring diffuse through the permeable coating, still allowing lustrous carbon defects to occur.

Effect of Mold / Core Baking - Test molds were baked to determine whether volatile binder components (solvents) influence the severity of lustrous carbon. Table 15 lists the results of baking tests on casting performance and binder weight losses.

Table 15: Effect of baking temperatures on lustrous carbon formation

Baking temperature	Mold appearance	Surface appearance – extent of surface wrinkling	% Binder loss	% Reduction in tensile strength
425^{O}F	Little to no color Change	2 – traces of surface wrinkling	25%	25%
500^{O}F	Deep chocolate brown Color	1.5 – no traces of lustrous carbon	55%	40%
Test conditions: 1.5% Phenolic urethane no-bake binder on Michigan lake sand (BOS) Pouring temperature – 2500^{O}F, pouring time – 25 seconds Baking time – 2 hours				

Test castings poured in molds baked at 425°F (218°C) for two hours exhibited some lustrous carbon defects, and no improvement was noted in comparison with non-baked molds. Test castings made in molds baked at 500°F (260°C) for two hours had excellent shakeout appearance, and the casting surfaces were free from lustrous carbon films and associated wrinkling defects.

Any of several chemical changes could occur in the binder by baking at 500°F (260°C). These include partial oxidation and elimination of constituents volatile at 500°F (260°C) or rearrangement of the cross-linked polymer. Any of these changes could be responsible for elimination of lustrous carbon from castings. It was noted that 500°F (260°C) baking changed the color of test molds to chocolate brown while baking at 425°F (218°C) produced little color change. Test cores baked at 425°F (218°C) for two hours exhibited weight losses corresponding to 25 percent of the total binder content. Given that as much as 10 percent of the binder weight can be volatilized during mixing from solvent loss, it is safe to assume that baking at 425°F eliminated all solvents. At the higher baking temperature of 500°F (260°C), weight losses corresponding to 55 percent of the original binder weight were obtained, indicating binder oxidation plays a significant role in lustrous carbon elimination.
The extent and degree of binder oxidation during pouring plays an important part in lustrous carbon elimination, as evidenced by the casting performance of binders having reduced carbon and increased oxygen levels.

Although post-baking at 500°F (260°C) was effective for lustrous carbon control, core or mold-strength degradation might limit the usefulness of this method. As Table 15 shows, baking at 500°F reduces the strength of cores by about 40%.

STEEL CASTINGS

Effect of Core Binders on Lustrous Carbon Formation - Results of casting tests to determine the effect of lustrous carbon formation on casting surface finish are shown in Table 16.

Table 16: Effect of core binders on lustrous carbon formation and surface finish in thin section steel castings

Binder	**Casting Appearance at Shakeout**	**Extent of Surface Defects**	**Surface roughness RMS (micro inches)**
PU No-bake (PUN)	Thin layer of adhering Sand	Moderate surface pockmarking	560 – 700
PU No-bake With 2% Fe_2O_3 (red)	Thin layer of adhering Sand	Smooth surface – no pockmarking	300
Furan No-bake (FNB)	Thin layer of adhering Sand	Smooth surface – no pockmarking	200 – 300
Phenolic Ester No-bake (PENB)	Thin layer of adhering Sand	Smooth surface – no pockmarking	120 – 200
Test conditions: Pouring temperature – 2900^{O}F, SAE 8620 Steel			

Thin-section castings made with PUN binders exhibited slightly pockmarked surfaces. Furan no-bakes and phenolic ester binder systems did not show any evidence of surface porosity. The best surface finish was obtained with the phenolic ester system, which had a surface finish of 120 to 200 RMS micro inches.

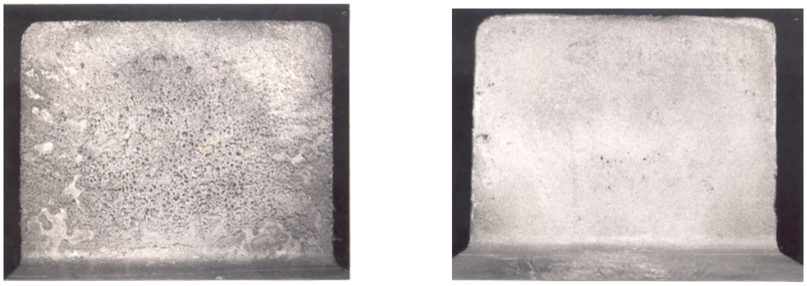
The addition of 2.0 percent red-iron oxide (Fe_2O_3) had a significant effect on eliminating the surface pockmarking associated with PUN binders. After the addition of iron oxide, the surface finish improved to 300 RMS micro inches. Uncoated furan no-bake test castings exhibited cast surface finishes between the PUN system and the PENB.

Casting results obtained with the heavy section Steel Founders' Society scab block casting are shown in Table 17.

Table 17: Effect of core binders on lustrous carbon formation and surface finish in heavy section castings

Binder	**Casting appearance at shakeout**	**Extent of surface defects**	**Surface roughness RMS (micro inches)**
PU No-bake	Thin layer of adhering Sand	Severe surface pockmarking	> 900
PU No-bake With 2% Fe_2O_3 (red)	Thin layer of adhering Sand	Smooth surface – no pockmarking	300
PU No-bake With 2% Fe_3O_4 (black)	Thin layer of adhering Sand	Severe surface pockmarking	> 900
Furan No-bake	Thin layer of adhering Sand	Smooth surface – no pockmarking	200 – 300
Test conditions: Pouring temperature – 2900^{O}F, SAE 8620 Steel			

PU No-bake binders without iron oxide additions exhibited severely pockmarked surfaces (Figure 9a).



a: PUN without iron oxide *b: PUN with 2 percent iron oxide*

Figure 9: Scab block castings made with phenolic urethane no-bake binders

The addition of 2.0 percent red-iron oxide (Fe_2O_3) was sufficient to completely eliminate defect formation (Figure 9b). Casting surface finish improved significantly to 300 RMS (root mean square) micro inches. Similar additions of black-iron oxide (2.0 percent Fe_3O_4) were not sufficient to prevent surface pockmarking. Furan no-bake binders (FNB) produced castings surfaces without pockmarking and with excellent surfaces of 200 to 300 RMS micro inches (Figure 10).

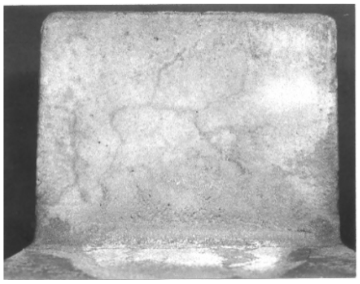


Figure 10: Scab-block castings made with premium quality furan no-bake binder, no iron oxide

These results clearly show the effects of iron-oxide mineralogy and chemistry. Although both iron oxides had similar mesh sizes (325 mesh x down), the red-iron oxide (hematite) clearly outperformed the black-iron oxide (magnetite). Although black-iron oxide additions are in common use today, much of the acceptance of black oxides is more likely related to surface area considerations. Sand additives having low surface area allow for less resin consumption and improved core-making economics. However, careful consideration must be given to the superior effectiveness of red-oxide in preventing porosity when choosing an oxide addition.

DISCUSSION

MECHANISM OF LUSTROUS CARBON FORMATION

Laps and Wrinkles – Iron Castings - Based on the physical appearance of lustrous carbon defects in castings and the effects of variables previously described, a reasonable description of the mechanism by which defects form can be proposed. As molten metal enters the mold cavity, thermal degradation of the binder produces hydrocarbon gases. The hydrocarbon rich vapor subsequently re-condenses as pyrolytic graphitic deposits in films or sheets on the mold-cavity surface**.** Figure 11 illustrates recovered deposits of lustrous carbon formed on test-mold surfaces during pouring.

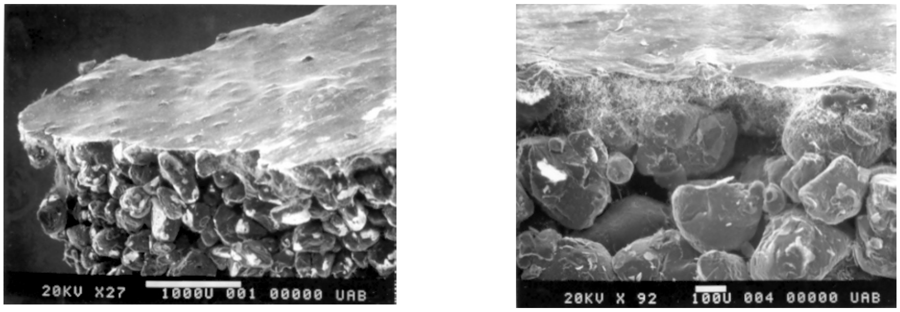


Figure 11: SEM Photographs showing a continuous carbon layer attached to the mold surface after metal pouring

As additional metal flows into the mold, these films may be flushed along ahead of the leading edge of the incoming metal stream, as illustrated in the schematic of Figure 12.

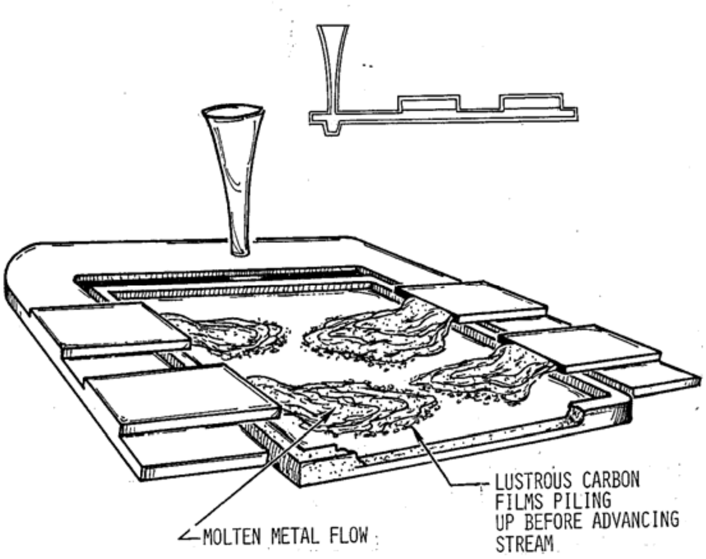
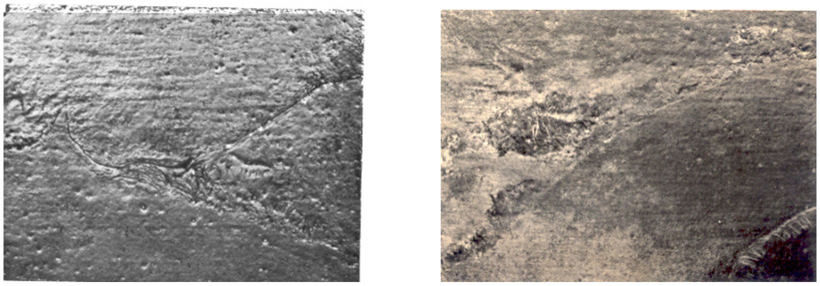


Figure 12: Metal flow pattern in test casting

These films can roll up to substantial thickness. If not dissolved in the metal or oxidized, solidification can proceed against the accumulation of carbon films. This gives rise to the characteristic surface wrinkling associated with lustrous carbon defects. Figures 13a and 13b illustrate test castings containing severe surface wrinkling. Examination of these casting surfaces indicates a strong tendency for defects to form along the edges of the first stream of molten metal that enters the mold cavity. Defects also tended to form in the ingate areas, as well as the sides and cope surfaces.



a. ***b.***

Figure 13: Examples of severe surface wrinkling from lustrous carbon formation in test castings

Under more severe pouring conditions, such as when using gating systems which produce turbulent flow and can cause cold shuts, lustrous carbon films can be flushed into the body of the casting or become sandwiched between two merging streams of molten metal. In severe cases, a laminating effect can occur that also might result in surface blistering. If the molten iron does not dissolve these films, they will prevent the welding of the merging streams of solidifying metal. A classic example of such a defect is illustrated in Figure 14 which shows a discontinuity extending almost 0.25 inch into the body of a gray iron casting.

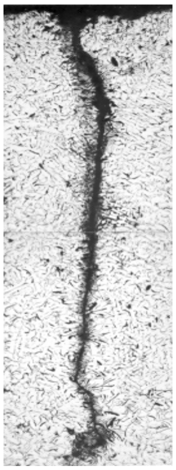
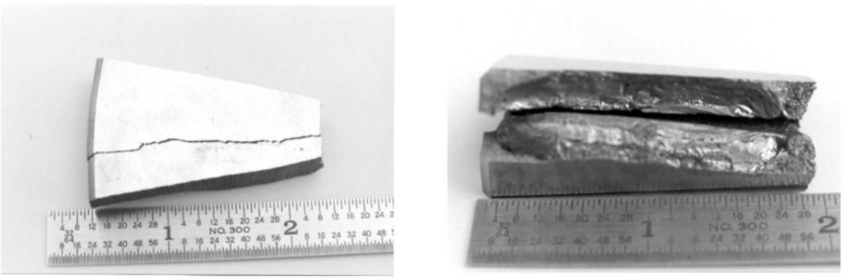


Figure 14: Microstructure of casting containing severe lustrous carbon "leaker" in gray iron,

This type of defect can be particularly troublesome in thin-section castings where hydraulic soundness and pressure tightness are important. Another example is the fractured section of the braking surface in an automotive disc brake shown in Figure 15. Merging streams of cast iron were prevented from welding together by lustrous carbon entrapment during casting. The defect was not easily visible after final machining but became noticeable during vigorous final casting inspection.



a. Top view of braking surface with defect ***b. Cross section of defect***

Figure 15: Automotive disc brake illustrating lustrous carbon defect extending across entire braking surface

It should be noted that the lustrous carbon forming tendencies of chemical binders is only harmful if large amounts of carbon films form and are subsequently dislodged from the mold-metal interface during pouring. When this happens, the characteristic wrinkling and surface laps result. If the lustrous carbon films are not dislodged during filling of the mold cavity, lustrous carbon formation may well be beneficial since casting surface finish will be improved.

Surface Pockmarking – Steel Castings - The appearance of lustrous carbon induced surface pockmarking in heavy-section steel castings suggests that a vigorous reaction occurs between the solidifying steel skin and carbonaceous by-products generated from binder decomposition (lustrous carbon). As molten metal enters the mold cavity, thermal degradation of the binder produces large quantities of hydrocarbon gases. The hydrocarbon-rich vapors subsequently re-condense as pyrolytic-graphitic films on mold cavity surfaces. These carbon films react quite readily with the oxidized semi-solid plastic steel skin. This localized carbon boil at the mold-metal interface results in severe surface disruptions or pockmarks (see Figure 16).

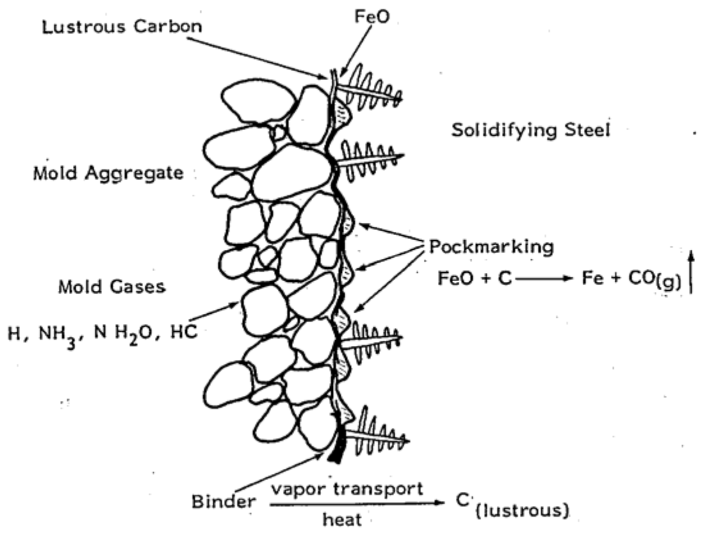


Figure 16: Proposed mechanism of pock making or surface porosity resulting from lustrous carbon reactions in steel

Additions of relatively pure, red-iron oxide (Fe_2O_3) to PUN binders are effective in eliminating lustrous carbon film formation and defects. Black-iron oxide (magnetite or Fe_3O_4) additions are not as effective in eliminating surface pockmarking. Other investigators have also shown that additions of Fe_3O_4 are not nearly as effective as hematite in controlled casting tests (Monroe, R.W., AFS Cured Sand Committee, Modern Castings 1982). Red-iron oxide apparently promotes the oxidation of lustrous carbon films generated from binder decomposition and / or retards the decomposition rate of the binder film on sand-grain surfaces (Hill, P.A.). Another reason why red-iron oxide is so effective in eliminating lustrous carbon is that it contains 2.43 percent more oxygen, 30.48 percent oxygen compared to 27.95 percent oxygen for magnetite.

In evaluating various grades of iron oxides, it should be noted that because commercial foundry grades of red-iron oxide are naturally occurring minerals, some deposits might not work as well as the grades used in these experiments.

RECOMMENDATIONS FOR LUSTROUS CARBON ELIMINATION:

The experimental results and the proposed mechanism of lustrous carbon formation suggest several techniques that can be employed to minimize or eliminate defects in casting operations. The best method for eliminating lustrous carbon is the employment of proper gating techniques. Accordingly, the following undesirable features should be eliminated from gating design: 1) employment of long, thin gates that enhance large metal temperature losses and 2) designs that maximize pouring time and/or turbulence.

In foundry operations where gating already is optimized or cannot be altered due to other limitations, other techniques may need to be used. If possible, pouring temperatures should be increased to at least 2700°F (1482^{o}C) unless metallurgical considerations, such as increased tendency for chill, structure limitations or casting soundness, prohibit use of high pouring temperatures (Naro, 1999). Secondly, the employment of suitable oxidizing additions to the sand mix, such as a minimum of 2.0 percent Fe_20_3 (red-iron oxide or hematite) should eliminate or greatly minimize lustrous carbon problems. In castings where lustrous carbon is still not controlled with oxidizing additions, larger quantities of 3.0 percent to 4.0 percent should be investigated. As a last resort, molds and cores could be baked at 500°F (260^{o}C) for at least one hour (or until the molds or cores change to a deep brown color) to drive off the volatile components of the binder that promote lustrous carbon formation.

With recent foundry concerns about the environment, foundries can use new phenolic urethane binders formulated with environmentally friendly biodiesel (vegetable-based oil) solvents to reduce lustrous carbon. Further, phenolic urethane binders that are formulated with solvents that decrease carbon and increase oxygen levels provide vastly reduced lustrous carbon levels.

CONCLUSIONS

For Iron Castings

1) High metal casting temperatures were found to eliminate the formation of lustrous carbon defects. The amount of lustrous carbon increased as the pouring temperature decreased. Pouring temperatures of 2700°F (1482°C) completely eliminated lustrous carbon in the experimental plate casting.

2) Rapid filling of the test mold cavity decreased both the severity and amount of lustrous carbon formed.

3) Binder levels and sand type had only modest effect on lustrous carbon formation, though washed silica sand minimized defects, presumably by restraining lustrous carbon films from being flushed away by flowing metal.

4) Offset binder ratios favoring minimal isocyanate levels (70/30, 60/40 and 50/50) have little effect on lustrous carbon defect formation. Excess un-reacted isocyanate tends to slightly worsen defect severity.

5) Red-iron oxide, yellow ochre, and aluminum sulfate were found to be effective in reducing lustrous carbon defects. These additions had only a minor effect on core properties at the levels studied.

6) Lustrous carbon defects were eliminated in test castings made with molds baked at 500°F (260°C) and with newly formulated phenolic urethane binders incorporating vegetable-oil based solvents, which contained reduced carbon and increased oxygen levels.

7) Venting and exhausting of carbon-laden gaseous decomposition products showed reduced levels of lustrous carbon defects.

For Steel Castings:

1. Incorporation of 2.0 percent red-iron oxide (hematite or Fe_2O_3) was effective in preventing surface pockmarking when phenolic urethane binders were used.

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