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Division of Physical Metallurgy
Steel Castings Section

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PROPOSALS FOR RESEARCH ON
GRAY CAST IRON

By

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* * *

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ABSTRACT

In accordance with a directive from the Bureau of Ships to investigate the effects of composition, microstructure and melting techniques upon the physical properties of gray cast irons, the literature in the field was comprehensively reviewed and prominent gray-iron metallurgists were interviewed. From information obtained from these sources, the unusual engineering properties of gray cast iron which cause it to be a very useful material for certain applications are described briefly and suggestions are made for various projects which are believed to be most beneficial for improving the properties and technology of gray cast iron. Broad headings of these projects are influence of alloys, constitution diagram, Maurer diagram, test bars, stress relief, gating and risering, correlation of electric furnace and cupola irons, classification of cast irons, effects of gases, and acicular irons. A list of those projects upon which some investigative work has been done is included.

AUTHORIZATION

1. An investigation to determine the effects of composition, microstructure, and melting techniques upon the tensile, impact, and fatigue properties of gray cast iron was authorized by BuShips Ltr. to NRL, Q/P Castings (334) dated 25 October 1943, Gray Cast Iron - Authorization of Investigation.

STATEMENT OF THE PROBLEM

2. The Navy has considered cast iron to be too brittle for applications on combat vessels. However, the rapid expansion of the Navy during the war was seriously handicapped by the inadequacy of steel forging, casting, and welding facilities to keep pace with military plans. It was soon realized that by proper applications of the engineering properties of cast iron, idle iron foundry capacity could be used to alleviate conditions in the overtaxed steel industry. As the Navy became more familiar with appropriate uses for gray iron, it became apparent that the many advances in iron technology during the past twenty years had established some desirable engineering properties which can not be obtained in any other material. The versatility of gray iron can be appreciated from the wide range of products made from it. At present some of the more important items include diesel and gasoline-engine crankshafts, camshafts, cylinder liners and sleeves, blocks, heads, pistons and piston rings; as well as crankcases, exhaust manifolds, flywheels, gears, housings, pump and compressor parts, valves, beds for machine tools, dies, pipes, and fittings. These castings range in size from piston rings weighing a few ounces to ponderous 62 ton turbine castings. Although the Navy has limited these applications to auxiliaries, landing craft, etc., it is possible that service records may eventually justify the use of gray iron in fighting ships.

3. In addition to an interest in direct military uses the Navy is also interested in civilian applications

for gray iron. Industrial progress in times of peace has provided a firm foundation for war production. Since war production creates critical shortages of essential civilian as well as military raw materials, substitutes occupy a dominant position in the war economy. During the emergency gray iron castings became important substitutes for other materials of construction fabricated by forging, welding, stamping, drawing or rolling.

4. Realizing the important role of cast iron in war production, the Navy authorized the Naval Research Laboratory to survey the field of cast iron to determine a program of experimental work which would be beneficial to the Navy. This report is an account of that survey. Some experimental work has been completed and will be reported in the near future.

SURVEY OF STATUS OF GRAY CAST IRON

5. A firm foundation for planning this program was first established by conducting a thorough review of all the literature concerning cast iron since 1930. This background of past experience, research, and development was supplemented by conferences with many of the leading cast iron metallurgists in the United States. Included in these conferences were:

- A. P. Gagnebin, Research Metallurgist, International Nickel Company.
- Dr. Tracey C. Jarrett, Chief Metallurgist, American Hammered Piston Ring Company.
- A. I. Krynitsky, Metallurgist, National Bureau of Standards.
- J. T. Mac Kenzie, Chief Metallurgist, American Cast Iron Pipe Company.
- F. G. Sefing, Metallurgist, International Nickel Company.
- James S. Vanick, Metallurgist, International Nickel Company.

Advisory Committee of the Gray Iron Founders' Society, Incorporated:

- T. E. Eagan, Chief Metallurgist, Cooper-Bessemer Corporation
- A. J. Edgar, Technical Secretary, Gray Iron Founders' Society, Incorporated.
- R. A. Flinn, Research Metallurgist, American Brake Shoe Company.
- W. W. Levi, Chief Metallurgist, Lynchburg Foundry Company.
- D. J. Reese, Metallurgist, International Nickel Company.

6. Inspection visits were made to the Grove City, Pa., plant of the Cooper-Bessemer Corp., the Baltimore, Maryland plant of the American Hammered Piston Ring Co., the New York City offices and the Bayonne, N. J. laboratory of the International Nickel Co., the Engineering Experimental Station, Annapolis, Md., and the Bureau of Standards, Washington, D. C.

7. From this background, there follows a summary of the engineering properties of gray cast iron, the advantages of fabrication, the more recent improvements of gray cast iron through research, and the research projects most worthy of attention at the Naval Research Laboratory.

Engineering Properties of Gray Cast Iron

8. To properly use cast iron, a thorough understanding of its fundamental physical properties is necessary. The characteristics of the basic stress-strain curve for cast iron differ considerably from that of steel. Unlike steel, gray iron does not follow Hooke's law exactly. Cast iron deforms elastically and plastically as an initial load is applied. The amount of permanent set remains constant at any load level but the ratio of stress to plastic strain decreases as the load increases. Thus, the modulus of elasticity is not constant but proceeds from a maximum at the lowest loading to a minimum at the point of failure, and the yield point is not well defined. Essentially all of the plastic strain takes

place in the first loading cycle so that in subsequent loadings iron acts as an elastic material. An increment of plastic flow will take place however when an applied stress exceeds that of any previous maximum stress. Cast iron has relatively low ductility as compared with steel. It does not elongate much in tension, bend greatly when loaded transversely, withstand strong shearing forces, nor endure high impact stresses.

9. Engineers usually design structures and machine components on the basis of the yield strength of the material involved. Since there is no distinct yield point as indicated by "drop of the beam" during the application of load in a tensile test of cast iron and since it is difficult to obtain the yield strength of cast iron by the offset method with conventional extensometer equipment, tensile strengths are usually the only strength values reported for cast irons. Flinn and Chapin have shown that the yield to tensile ratio of cast irons may be as high as 0.9 when the yield strength is measured by intersection of the stress-strain curve and a line drawn parallel to the tangent modulus at 0.1 percent offset.^{1/} Therefore, it would appear that cast iron is better suited on the basis of yield strength for certain applications than might be believed.

10. Cast iron behaves as a ductile rather than a brittle material in its ability to deform very slightly in a plastic manner at all levels of stress. By this so-called property of "crackless plasticity" gray cast iron is enabled to carry occasional overloads without cracking by redistribution of sudden concentrations of stress by plastic flow.

11. The compressive strength of cast iron is usually two or three times greater than its tensile strength whereas for steel these two properties are about equal to each other. For gray iron the range of compressive strength is 70,000 to 200,000 pounds per square inch.

12. The presence of graphite in gray iron is accountable for a number of its unique properties. Flakes of graphite act as insulating voids and break up the structure to make a heterogeneous material. This condition gives gray iron a superior capacity for damping vibrations in machinery and consequently for minimizing the potential danger of allowing critical harmonic stress to be concentrated in local areas.

13. Compared with steel, the impact resistance and endurance limit (fatigue strength) of iron are reduced much less by the presence of necessary or accidental notches, such as oil channels, keyways, fillets, screw threads, tool marks, etc. For example a radial hole in a cast iron specimen reduced the endurance limit only 13 percent compared to a reduction of 67 percent in steel² under similar conditions. This notch insensitivity of gray iron is attributed to graphite flakes which act as many notches dispersing stress concentrations from any one location.

14. The ability of graphite in gray iron to absorb the expansion and contraction of thermal shock makes it especially suited for ingot molds, dies for glass molding, certain furnace parts, rolling-mill rolls, etc.

15. Gray iron is used extensively for applications such as piston rings, cylinder liners, brake shoes, dies, etc., where the surface of the part is subjected to rolling or sliding friction. The particles of graphite in iron act as lubricants by themselves. Moreover, as these friable particles are worn or chipped away in service, the resulting voids serve to hold oil or other artificially applied lubricants at the bearing surface. For these reasons, gray cast iron is particularly resistant to galling and seizure between moving parts.

16. From this review of the physical properties of cast iron the importance of making a detailed analysis of the critical stresses to which the metal will be exposed is obvious. The intangible key to improving machines and structures by the use of cast iron is a willingness on the part of designers to understand the limitations and advantages of gray cast iron.

Advantages of Fabricating Gray Cast Iron

17. Gray iron castings are relatively inexpensive. Pig iron and scrap iron, the basic raw materials, are cheaper than other metallic materials. Moreover, the melting equipment, such as the cupola and air furnace, are cheaper to install, maintain, and operate than corresponding equipment for steel foundries.

18. The properties of gray cast iron are conveniently insensitive to the presence of the impurities, sulphur and phosphorous, in the range generally encountered in raw materials of this country. While specifications for steel generally limit these two elements to a maximum of about 0.05 percent, specifications for gray iron usually allow at least 0.10 percent sulphur and 0.20 percent phosphorus.

19. The excellent fluidity of iron coupled with low shrinkage permits a wide range of intricate and hollow shapes with various cross-sections to be cast with success. Several examples are engine blocks, steam chests, crankshafts, radiators, etc.

20. A major factor in the economy of fabricating gray iron is its excellent machineability attributable to graphite which permits higher turning speeds and heavier cuts with reduced tool wear.

Recent Progress Through Research

21. Since about 1930 the interest in cast iron research has been slowly increasing until today a number of organizations have set up long range programs on this subject. A few of the more important groups are the U. S. Bureau of Standards, Battelle Memorial Institute, International Nickel Company, and American Brake Shoe Company. A number of other companies and universities are similarly engaged. As a result, many old theories have been supplanted by newer ideas and many heretofore unexplained phenomena have been carefully investigated. Foundry practice is constantly being improved but this progress is very slow and often continues unnoticed. Fortunately, progressive foundrymen usually publish summaries of new development made within their plants.

22. The direction of cast iron research at present is determined by the needs of the industries sponsoring the work and is naturally influenced by the profit motive. Each company designs its research to sell its products. For example, considerable research has been conducted by the alloy manufacturers on the effects of alloying elements in iron, and, naturally, data showing the advantages of alloys are published whereas other data may be held without publication. Even the research at the Battelle Memorial Institute is instigated and

sponsored by industrial organizations. The Gray Iron Founders' Society, Inc., has fostered an unbiased program to encourage gray iron research for theses in various colleges and universities by offering prizes for the best papers. Subjects suggested by the Society for investigation include:

- Creep values of gray iron at 600 - 800°F.
- Elongation of gray iron.
- Impact values of gray iron.
- Machinability of gray iron.
- Modulus of elasticity of gray iron.

23. Since graphite is the constituent of gray cast iron which most distinguishes its metallurgy, it is not surprising that much of the research has been on the subject of graphite. The origin of graphitization during the solidification of cast iron has been traced to nucleation which may be accelerated by certain elements such as silicon. For optimum properties in gray iron, the graphite flakes should have a random distribution. However, the graphite flakes often assume an undesirable dendritic distribution referred to as Types D, E, eutectiform, or grain-boundary graphite which precipitates in the austenite grain boundaries and creates planes of weakness.^{3/} Research and practice have shown that increasing the time and temperature of holding iron in the furnace causes more of the graphite nuclei to be dissolved so that the tendency for grain boundary graphite to form is greatly increased.^{4/} The recent practice of inoculating molten iron with flake graphite, ferrosilicon, calcium silicide, silicon metal, or alloy combinations of silicon, nickel, chromium, manganese, titanium, zirconium, aluminum and/or copper has been successful in altering, modifying, or eliminating grain boundary graphite, free ferrite, iron carbide, and related irregularities in structure and physical properties. These elements act as graphitizers, deoxidizers, and/or degasifiers. The inoculating addition may vary from 0.10 percent to 0.75 percent or more of the total weight of the metal and is made to the melt or ladle from two to thirty minutes before pouring.^{5/6/7/} There are three theories which have been proposed to explain the functions of inoculants. They are known as the "graphite nuclei" theory, the "silicate slime" theory and "gas" theory.^{8/9/} Papers have been written to prove or disprove all three theories so that there is not a unanimous acceptance of any of them.

24. The American Foundrymen's Association sponsored a project to classify the many sizes and shapes of graphite. As a result a set of standard charts now identify five different types of graphite flakes, Types A - E, and eight different sizes of graphite flakes, Sizes 1 - 8. 10/

25. The recent investigation of R. A. Flinn and D. J. Reese has revealed a substantial improvement in the matrix of cast iron. They discovered that cast irons with an effective carbon below 3.6 percent and a minimum of 0.50 percent molybdenum and 1.5 percent nickel could be given an acicular matrix by austempering. Irons so treated have tested as high as 100,000 pounds per square inch in tension, have excellent fatigue resistance ranging from 18,000 to 25,000 p.s.i., and are especially suited for cast crankshafts and other highly stressed machine parts.^{2/}

26. Since the major portion of all cast iron is produced in the cupola, improved practice in this type melting unit has broad benefits. Recent developments such as using larger percentages of steel in the charge, continuous tapping into a heated forehearth, installation of kindling tuyeres, and use of a hot blast with controlled moisture content have made it possible to produce 2.75 percent carbon iron on a production basis and even lower percentages can be foreseen. 11/12/

27. From this background of recent progress in the metallurgy of cast iron, a critical analysis can be made of the important channels into which future research should be directed.

Recommended Fields for Future Research.

28. Because there has been practically no inspiration for fundamental research in the field of the metallurgy of cast iron, the effects of variables have frequently been observed without determinations of basic causes. In spite of centuries of use, the basic principles of the metallurgy of cast iron still border on the occult.

29. Influence of Alloys. The influence of the alloys on the physical properties of cast iron are summarized in the Cast Metals Handbook and the Alloy Cast Iron Handbook. Establishing these effects of specific alloys was only a matter of routine investigation. However, ascertaining the reason for these effects is important work which is the key to predicting

accurately the influence of each element in any alloy combination without resorting to the lengthy and expensive system of trial and error.

30. Constitution Diagram. The present iron-carbon constitution diagram is not particularly useful to the metallurgist who is concerned with cast iron. Gray iron is a hybrid which may solidify in the stable iron-graphite system or in the metastable iron-iron carbide system or in a combination of both. There is an ever-growing need to know more about the control of these systems by variations in chemical composition, melting practice, inoculation, and cooling rate. Careful work is needed on the liquidus-solidus-eutectic zone of cast iron. For example, there is needed a practical working iron-carbon-silicon-temperature diagram constructed for irons containing manganese, sulphur, and phosphorus in amounts common to the industry. The effects of melting practice, inoculation, and cooling rate on this diagram should then be thoroughly explored. Once established, the functions of other alloying elements could be studied more logically. Corollary with this project, a better understanding of the mechanics of graphitization in the freezing zone of cast iron might be derived. Likewise, knowledge of the rate of iron solidification or skin growth would aid the metallurgist to control more accurately the quality of his castings.

31. Maurer Diagram. The original Maurer diagram, a plot of carbon versus silicon for various cross-sections with completely pearlitic matrices, has been antiquated by the wide-spread practice of inoculation. A new revised diagram of this type for inoculated irons would be very useful.

32. Test Bars. During the war there has been considerable criticism of Navy specifications and tests for cast iron by the foundries. A long range program to improve the quality and type of standard arbitration and tensile test bars would go far toward stopping the rejection of many good castings and acceptance of many poor ones arising from non-representative tests. An exacting foundry technique should be developed to produce sound test-bars which yield consistent values in physical testing. There is a growing need for a good impact test and specimen to replace the present ones designed primarily for steel. Closely related are problems inherently characteristic of iron, namely, reducing the section sensitivity of cast iron and correlating the physical properties of castings and test bars of varying cross-section.

33. Stress Relief. As a result of section sensitivity, castings with intricate shapes are apt to be weakened by many "as cast" stresses. Similarly, many castings are warped when the skin is removed by machining. Allowing the casting to age as long as a year before machining usually relieves this inclination to warp. Because of these tendencies, stress relief heat treatments are very beneficial for many gray iron castings. However, there is practically no information available on the proper stress relief cycles for the many plain and alloy irons requiring treatment. The relaxation machine at the Naval Research Laboratory is ideal for obtaining these data which industry needs. The effects of stress-relief treatments on the physical properties of irons would be a valuable adjunct to the project.

34. Gating and Riser. By the use of insulation around the risers of non-ferrous castings foundrymen have been able to reduce the size of risers and to produce castings with less porosity and with fewer tucks and draws. Perfection of a riser insulator for cast iron and studies of the feeding capacity of risers for gray iron castings would be equally valuable. Since no two foundrymen ever agree on the proper way to gate and riser the same casting, proper techniques need to be established.

35. Correlation of Electric Furnace and Cupola Irons. Foundries have always been reluctant to accept and apply to cupola irons the results of laboratory research obtained from electric furnace irons. Although both irons may have the same chemical composition they do not have the same solidification characteristics or physical properties. Irons melted in the electric furnace have a stronger tendency to solidify with Type D and E grain boundary graphite than cupola irons. The reasons for the differences between cupola and electric furnace irons deserve thorough study and a knowledge of them would be very helpful in the practical application of laboratory research. A few of the questions which warrant attention are:

Can electric furnace irons be made comparable to cupola irons?

What superheat temperature in the electric furnace would be equivalent to that of the cupola?

Do gases in the cupola act as metal inoculants?

Can the cupola atmosphere be duplicated in electric furnace melting?

In what way do the microstructures and physical properties differ in irons of the same composition from cupola and electric furnace?

36. Classification of Cast Irons. Considerable confusion exists in the cast iron industry because no workable or commonly accepted system of classification has been established for the numerous plain carbon and alloy irons which are produced. Many of these grades have identical or very similar properties and it is believed that specifications could be simplified and standardized to a large extent by classification in much the same way that the Society of Automotive Engineers standardized the classification of carbon and alloy steels many years ago. Procurement of gray iron castings in times of emergency would be expedited considerably by common usage of a simple and workable classification system.

37. Effects of Gases. The effects of dissolved gases in metals have always been difficult to establish. Although the important influence of H_2 and CO on the properties of cast iron is realized, it is not clear how these gases bring about their effects. Hydrogen is derived from water vapor and favors the formation of flake graphite and inhibits ferrite formation. Carbon monoxide is formed by the reduction of silica by carbon or by the reaction of carbon with air. It promotes Type D and E grain boundary graphite and ferrite. A systematic study and correlation of the influence of furnace atmosphere and lining, slag and metal composition, melting practice, and raw materials on gases in cast iron would be a valuable addition to the knowledge of the metallurgy of cast iron.

38. Acicular Iron. For a multitude of important applications, such as crankshafts, the use of nickel-molybdenum alloy cast irons with an acicular matrix has been accompanied by many production problems. Although this type of matrix can be obtained from electric furnace iron with low carbon content, it is very difficult to produce in the higher carbon irons made in the cupola. At present cupola iron castings must be air-cooled through the eutectoid zone to obtain the desired matrix. Alloy combinations which would cause the formation of the acicular structure in castings of high carbon iron cooled in the mold would open a broad field to the majority of foundries which operate cupolas. The favorable effects of boron on hardenability of steel merits an investigation of its influence on acicular-type cast irons.

CONCLUSIONS

39. As a result of an extensive literature review and numerous conferences with experienced metallurgists, it is believed that a broad program of fundamental research on gray iron should include such projects as the influence of alloys, the constitution diagram, the Maurer diagram, test bar, stress relieving, gating and risering, correlation of electric furnace and cupola irons, and effect of gases.

40. Research Work on Gray Iron Now in Progress at NRL.
The following gray iron research projects are now in various stages of development at the Naval Research Laboratory:

- a. Mode of Solidification and Rate of Freezing of Cast Iron.
- b. Improved Navy Test Bar Specifications for Cast Iron.
- c. Stress Relief Treatment of Cast Iron.
- d. Procedures for Melting Cast Iron in Oil Fired Crucible Furnaces.
- e. Insulating Riser Sleeves for Ferrous Metals.
- f. Gating and Risering of Gray Iron Castings.

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