THE UNIVERSITY OF MICHIGAN

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THE RELATION OF ENGINEERING PERFORMANCE OF CASTINGS TO METAL STRUCTURE

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SUMMARY

The performance of a casting depends upon five principal variables: (1) Service conditions, (2) Design, (3) Residual stresses, (4) Soundness, and (5) Metal structure. After illustrating the importance of the first four subjects, major attention is devoted to the relation of performance to metal structure.

Examples of the correlation of performance with structure are given in the following fields: (1) General engineering properties such as mechanical properties, (2) Wear and Abrasion, and (3) Heat and Corrosion Resistance. It is established that if other variables are kept constant, engineering performance depends uniquely upon the structure. Substantial improvement is possible by observation of the effect of nature, amount, size, shape, distribution and orientation of microconstituents.

INTRODUCTION

At this International Congress devoted to the broad theme of "The Foundry at the Service of Man", it seems proper to devote a portion of the time to a review of recent technical advances as well as to original research. By critical consolidation of information new lines of research can be stimulated as well as placing the principal findings of recent work in proper focus for use by the engineer and designer.

In the cast metals field significant new developments have taken place in many spectacular directions such as automation and the growth of new melting and molding methods. Less spectacular but equally important has been the gradual acquisition of a better understanding of the principal factors governing the performance of castings in service. It is to this point that this paper is devoted.

The consumer as well as the designer is coming to appreciate the economic fact that the value of a casting depends not upon it weight nor chemical analysis but rather upon the cost per hour of safe, useful service. It is the growing acceptance of this criterion of performance that has nourished the development of many new and even exotic alloys as well as variety of changes in design and casting practice.

What are the general variables which determine casting performance? There are only five of importance:

I. Service Conditions
II. Design
III. Residual Stresses
IV. Soundness
V. Metal Structure (Macrostructure and fine structure).

While these will be discussed in the above order, it should be pointed out that in the development of a casting for a given appreciation, these variables must be considered concurrently. A change in design may, for example, change the efficacy of splash lubrication in an engine or result in a difference in heat transfer which could alter the performance of a given metal structure. In other words, these five are not usually independently variable.

I. Service Conditions

An engineer is continually reminded in his private life of the importance of controlling service conditions - as for example when another member of the family reports excessive oil consumption in the family car but does not mention the disastrously variable oil level preceding this observation. The same engineer, however, in his professional life is often guilty of assuming that three engines from the same manufacturer, installed at the same time, should exhibit identical performance, regardless of the activities of the night shift.

Under service conditions then, both the regular and irregular environments of the part must be considered. At this point, it is well to take note of the recent healthy change in the philosophy of specification of materials and even in design. The attitude used to be that if the most expensive materials and the most generous and consequently the heaviest sections were used, the machine should be expected to deliver optimum performance. This has changed to the philosophy of "letting the machine tell the engineer" the best material and the best design. In other words a group of possible materials is service tested and, in truth, the machine indicates its preference. A parallel in design will be discussed later.

The comparison of materials under service conditions in this way should not however be a passive, routine study. By imaginative and comprehensive examination of failed and partly failed parts, the reasons for breakdown may be determined. Once the mechanisms of the failures which limit service life are known, new metal structures and new designs can be developed.

Service requirements may be divided into the following broad groups: General physical properties; Wear and abrasion; Heat and corrosion resistance.

Since this review is concerned with engineering properties, the role of color, style and other aesthetic values will not be considered.

The development of metal structures for these different service conditions will be discussed in Section V.

II. Design

Although the principal emphasis of this review will be upon the interrelation of metal structure and performance, the role of design must be mentioned briefly for completeness. In many cases too much effort has been devoted to improvement of materials for a particular part when a design change would be more desirable. Broadly speaking, it has generally taken at least a decade of research to develop new alloys of a given base metal with an improvement in strength of 50-100%. By contrast, a small design change, such as the removal of a hole or sharp fillet, can improve the allowable working load of a component by 300%.

Two recent advances have been of vital importance in the greater acceptance of castings for critical parts:

1. The development and use of new techniques of experimental stress analysis.
2. The trend toward guaranteed mechanical properties at specified locations in the casting.

The first topic may be discussed here, reserving the second for Section IV, Soundness.

It is generally admitted that castings can be made more easily in complex shapes and contours than many welded assemblies or forgings. Classical design procedures have not taken advantage of the better stress distribution which is possible with complex contours because the calculations are often difficult or indeterminate. As a result many casting designs reflect the simpler calculations which are possible by combining cubes, cylinders and spheres rather than the reduced stresses which result from skillful blending of irregular sections. With the advent of easily applied resistance strain gages and brittle lacquer but still employing the general reasoning of engineering mechanics, it has become possible to visualize the strain distribution throughoughout the most complex structures. By the adroit use of models coupled with actual measurements under service conditions, much advanced work has been done in this field.

As an example a design study of a large crankshaft section is illustrated in Figure 1. The change in internal contours and fillets which is possible in the cast as compared with the forged and machined design results in a change in stress of 14% and greatly improved stress distribution.

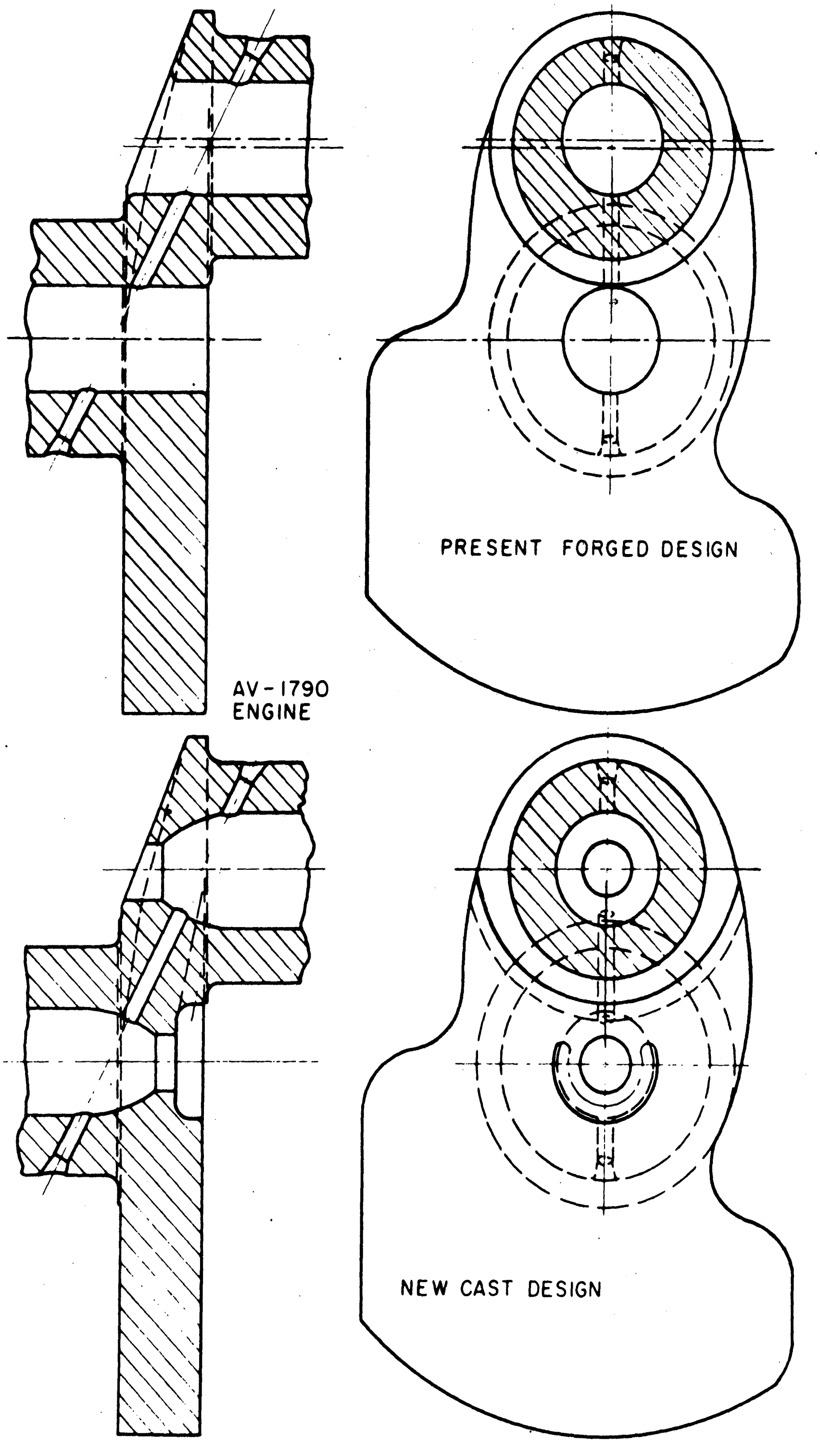


Figure 1. Comparison of Cast and Forged Crankshaft Designs for Large Crankshaft

III. Residual Stresses

Until the engineer comes face to face with a catastrophic failure resulting from residual or "internal" stresses, he usually gives this variable only cursory attention in the interpretation of service behavior. This attitude changes rapidly after he has been called upon to explain the rupture of a large complex shape such as a lathe bed which has occurred merely resting overnight on the foundry floor or during shipment to a customer, or, worst of all, during the initial service run under light loads. It is an enlightening experiment to cut test specimens from a part which has failed in this manner and obtain values well above specification, say of the order of 100,000 psi for a cast steel, and realize that the service stresses which caused failure were one tenth of this magnitude. The balance of the breaking load is, of course, supplied by the residual stress. This stress has been caused either by thermal gradients or uneven phase transformations during cooling or subsequent processing.

The relief of these residual stresses or even better, redistribution in a favorable direction, is related to the metal structure concerned and will be described in Section V.

IV. Soundness

This variable is sometimes discussed along with metal structure since the thermal history which is related to structure can be closely associated with the resulting soundness. However, if the behavior of sound metal structures is to receive proper consideration, the effects of porosity are best covered separately.

The principal reason for the absurdly low design stresses for castings in the average handbook is because of the variation between properties of test bars and castings. There is no reliable factor relating a *sound* test bar to an *unsound* casting and furthermore it must be recognized that such a factor is unobtainable. As a result of the excellent quantitative work of many investigators, it is now possible to make any desired section or sections of a casting free of porosity.

The general term porosity is used because it stems from two principal sources - gas and liquid to solid shrinkage. Harmful gas evolution during freezing is now avoided by control of the variables in melting, ladle treatment, mold design and material and in pouring practice. Avoidance of shrinkage cavities by control of solidification pattern is now possible for even the most difficult materials to feed.

It can now be stated categorically that the mechanical properties at a given region of a casting (naturally the highest stressed region will be chosen) can be made equal to those of a test bar of *the same cooling rate*. In other words, if the metal is sound and cools at a given rate it has no way of knowing whether it is in a test bar or casting. Much of the confusion comes from the philosophy emphasizing that the test bar represents only melt quality. The test bar indeed provides a good check of melt quality but it should also represent the properties of a sound casting of the same heat of the same cooling rate. Otherwise, unfair and unwarranted variables such as differences in pouring temperature, deoxidation, or mold material have been used in the test bar preparation. In addition to test bars from a given heat, the designer should have access to data showing the variation in properties

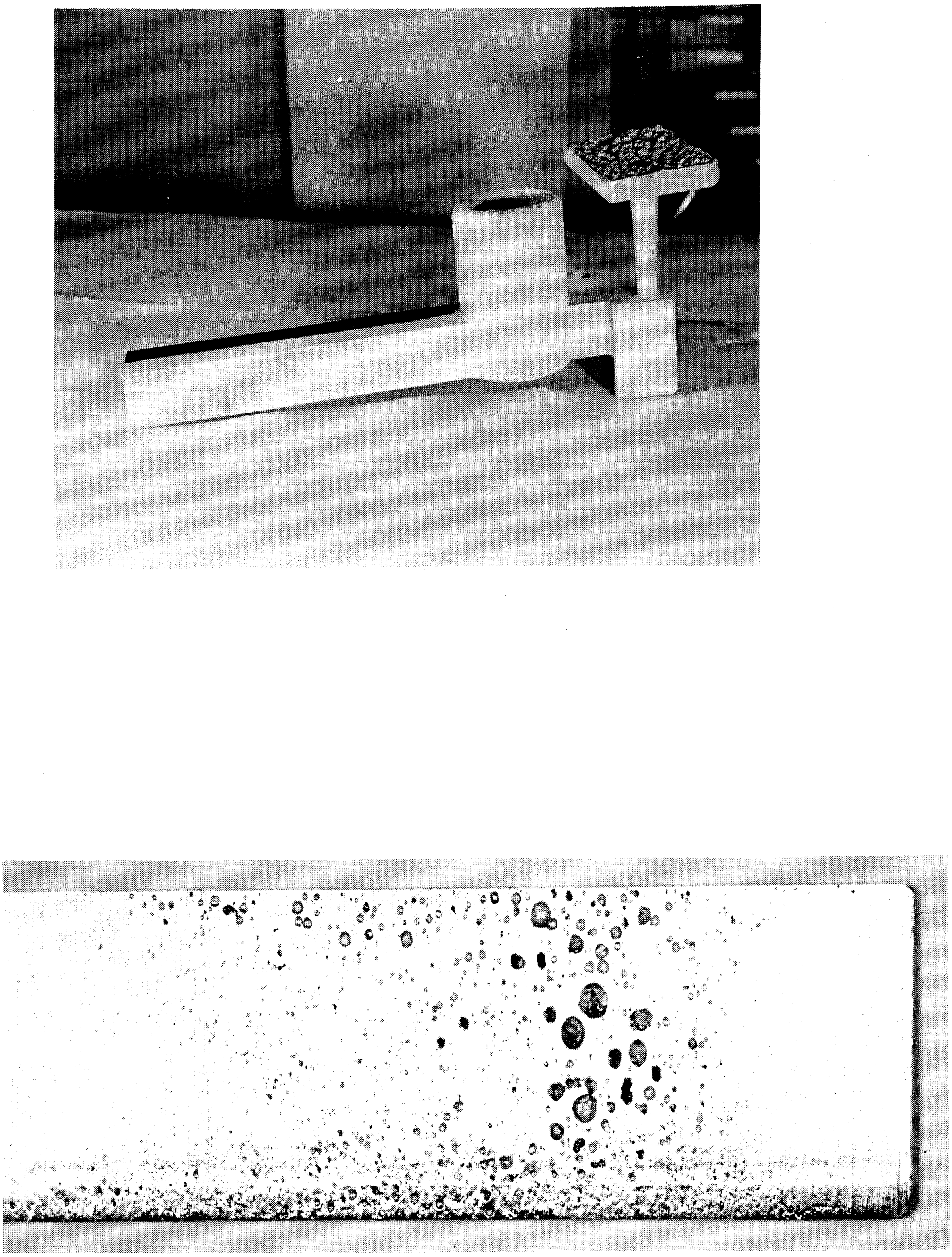
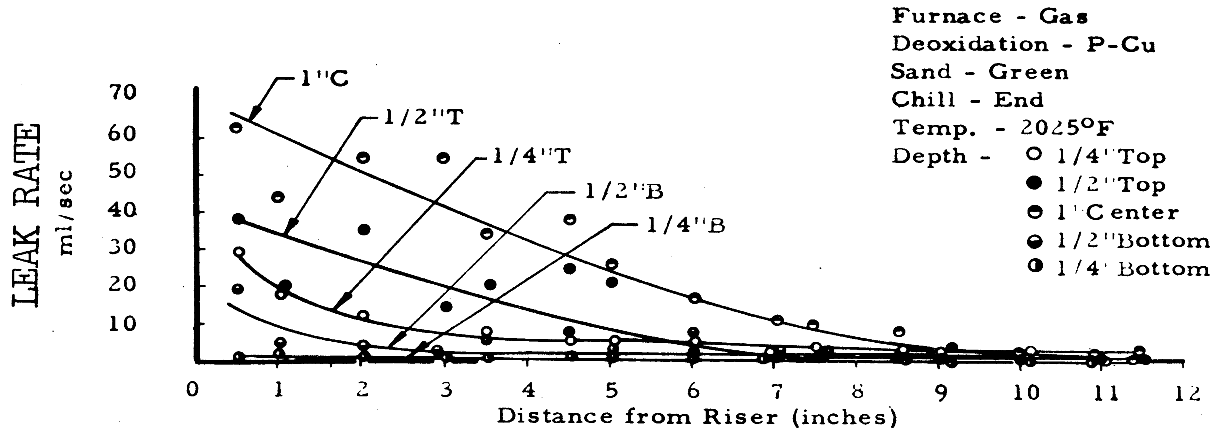


Figure 2. Porosity Due to Mold-Metal Reaction Associated with High Pouring Temperatures



2.6% MOISTURE - GEOMETRICAL DISTRIBUTION OF LEAKAGE

H-21 Bar 4

Figure 3. Effect of End Chill Upon Porosity in 85-5-5-5 Bronze Test Bar

(The porosity is measured by the rate of gas flow through a 1/32" thick test section machined from the centerline of the bar. Minimum leakage is encountered at the chilled end where the thermal gradient during solidification was at a maximum.)

with cooling rate (section size). For some materials such as gray iron this is a highly significant effect, for heat treated materials such as cast steel or ductile iron the variation is slight at constant combined carbon.

As an example of the control of porosity caused by gas and shrinkage the illustrations of Figure 2 and 3 may be considered briefly. It is generally agreed that 85Cu-5Pb-5Zn-5Sn alloy often provides a problem in certain castings in which "pressure tightness" is required. In recent work(1) sponsored by the Brass and Bronze Division of the American Foundaryman's Society, the occurrence of both types of porosity is illustrated in an interesting manner. When 85-5-5-5 alloy is poured at excessive temperatures, spherical porosity is encountered particularly in the upper regions of the test bar, Figure 2. This gas is a result of mold-metal reaction. At lower pouring temperatures, the porosity is essentially of the interdendritic centerline shrinkage type which can be altered or removed by the imposition of proper thermal gradients during solidification, Figure 3.

V. Metal Structure

The principal division of this paper, the relation of performance to metal structure, may now be discussed in its proper perspective. The other four divisions just presented are of vital importance in interpreting properly the effects of changing the metal structure. It would, for example, be a mistake to heat treat a casting to change the structure and double the tensile strength, if in so doing the residual stress were raised to 90% of the new tensile strength (assuming of course the critical service stresses were tensile).

An additional reason for this prior emphasis on the other variables is that metal structure can be the most expensive to change. If abusive service conditions, such as poor lubrication, can be remedied by proper design or maintenance, this approach is usually more economical than employing an expensive wear resistant alloy. Finally, the elimination of residual stresses or often better still, their control and proper redistribution can be a simple matter in many cases compared with the expense of a new material.

In any event, some material will be needed and maximum engineering skill in using it properly may be assumed. How is the material to be selected?

If the four variables just discussed are kept constant the performance of the component will then depend uniquely upon the metal structure. As an important corollary, if components made of the same structure do not give comparable performance within statistical limits, the other variables are not being kept constant regardless of all appearances. Notice particularly that it is not stated that castings of the same chemical composition and mechanical properties will necessarily give the same performance. What is meant then by castings of the "same metal structure"?

To describe the usual metal structure containing two or more phases, six variables must be specified:

Nature)
Amount)
Size) of phases present
Shape)
Distribution)
Orientation)

Examples of these variables may now be considered.

Nature of phases. The detail required here will vary. In an annealed gray iron for strictly mechanical use, a machine tool base for example, it may be sufficient to know that the matrix is a solid solution of silicon in body centered cubic iron with flake graphite of a certain type and distribution. In a wrought silicon transformer steel, however, more detail would be needed. The prior plastic deformation and the domain structure of the ferrite would be of importance in understanding the magnetic properties. In a heat resistant alloy the degree of ordering might be significant, requiring X-ray diffraction analysis.

Amount of phases. This obvious variable requires little clarification except to emphasize that estimates of amounts by qualitative observation can be very misleading. Several excellent quantitative point counting methods are now available.

Size of phases. In single phase alloys the grain size is one of the more important variables. Some of the effects which have been attributed to grain size are now suspected to be caused by trace elements at the grain boundaries, but in recent years it has been assumed that if A is soluble in B in the solid state, a uniform dispersion on an atomic scale of A in B will result. It is now found that impurity atoms will separate at grain boundaries and other defective regions in the lattices even though present in amounts below the "equilibrium" solubility. These effects are also present in two phase alloys.

Shape of phases. As an example of this effect, one of the most important recent advances in cast alloys has been the controlled production of spheroidal graphite in the cast condition in gray iron. The resulting change in properties from a material low in strength and ductility to a ductile alloy with properties approaching steel in a fascinating chapter in metallurgical history and will be discussed shortly.

Distribution. This variable is often related to the other factors since the same heat treatment process which may be used to change size and shape will often change distribution. The alteration of the grain boundary carbide in hypereutectoid steel by heat treatment is a classic example.

Orientation. Pronounced directionality of properties is encountered with preferred orientation. In the past, major attention has been given to the presence of preferred orientation in wrought materials such as cold rolled plate and cold drawn wire. Recently, however, much interesting work has been done on the orientation in cast structures particularly in zone melted and refined semiconductors.

Engineering examples

To illustrate the application of the foregoing discussion of the principal variables determining engineering performance, a number of illustrations of different service conditions may now be considered.

To obtain the widest variety in these discussions it can be agreed that different types of engineering applications may be divided into the following groups as described earlier:

1. General engineering applications. These require certain physical properties, e.g. mechanical properties such as tensile strength, ductility, endurance limit such as a crankshaft. Electrical magnetic, thermal properties are also included here.

2. Wear and abrasion resistant materials. There is no general quantitative relationship between these complex applications and physical properties. In each application, however, there is a metal structure which will give reproducible, maximum performance.

3. Heat and corrosion resistant materials. These two groups of applications are classed together because there are similarities in the oxidation process. Other features, however, such as creep and thermal shock are quite distinct. Less is known of the mechanisms involved in these alloys and principal attention will be given to classes 1 and 2.

1. General applications requiring specific physical properties.

As illustrations of this type of performance of the metal structure perhaps the most common are those involving mechanical properties. In passing, it should be mentioned that very significant and rapid advances in electrical and magnetic properties are being made via a study of vacancies and impurities in metals and semiconductors. For the present purpose however, simple illustrations will be drawn from mechanical properties interpreted in the light of the behavior of the microstructure under stress.

One of the clearest illustrations of the effect of the nature, shape and distribution of phases may be obtained by comparing the properties of gray and ductile irons. Let us first review the mechanical data, Figures 4A,B and then observe the mechanism of flow and fracture, Figures 5A,B.

Referring first to the properties of the gray irons of different matrices it is evident that the materials with a single phase matrix (either ferrite or austenite) exhibit the greatest ductility. The same effect is noted for the ductile irons. As the carbide phase is added the highest

DUCTILE CAST IRON

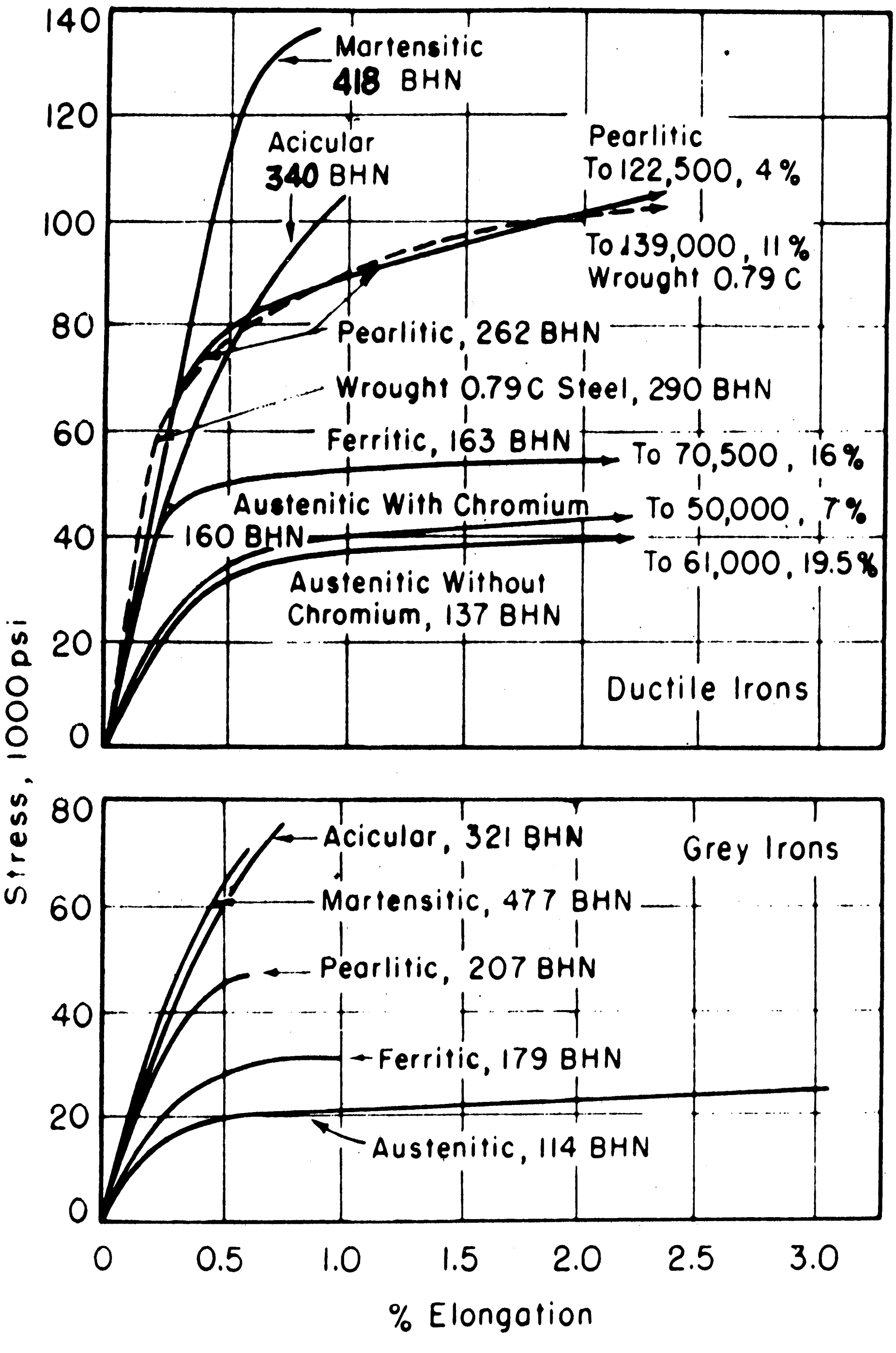
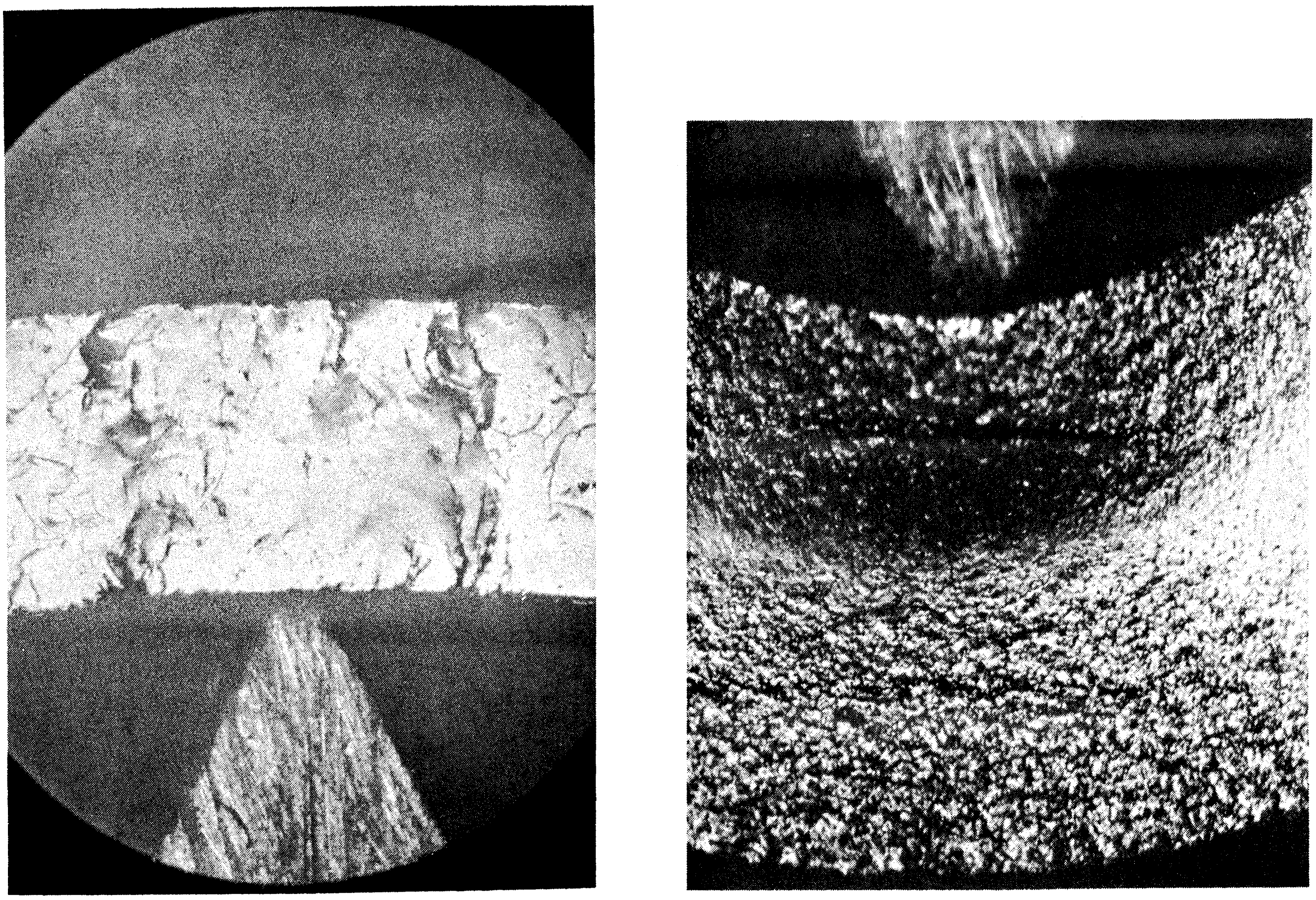
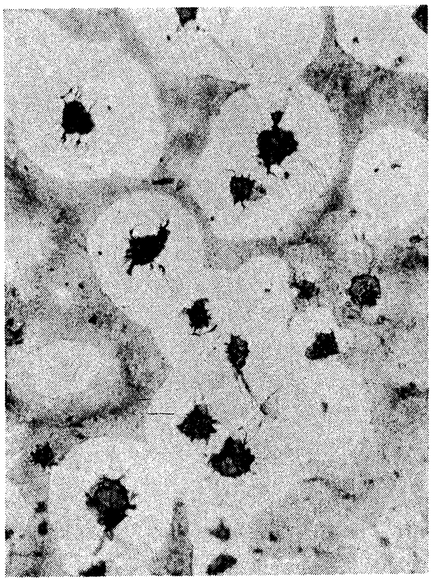


Figure 4. Tensile Stress-Strain Curves for Ductile Iron and for Gray Iron of Comparable Matrix Structures.



A

B



(Microbend stressing of ductile iron with ferrite and pearlite- 500X, nital etch)

C

Figure 5. Behavior of Gray and Ductile Iron Structures During Microbend Stressing. (A. Ferritic gray iron; B. Ferritic ductile iron. Center of Beam loaded as shown by knife edge. Approx. 50X).

hardness and strength are obtained as the mean free path between carbide particles reaches a minimum. This also corresponds to minimum particle size (in the range investigated). Now by comparing the properties of iron with similar matrices but with different graphite shape (flake vs. spheroidal) the role of particle shape is apparent. The change in shape results in 5 to 20 times the elongation and from 2 to 3 times the tensile strength. Hardness is affected to a minor extent.

The progress of flow and fracture is evident in the photomicrographs of Figure 5 which were taken during testing in an instrument called the "Strain Viewer".(2) A small beam of material (1" x 1/16" x 1/16") is cut to size, mounted in thermal setting plastic and polished on one 1" x 1/16" face. After removing from the plastic it is placed in the strain viewer and bent while being observed through the metallurgical microscope, The progress of slip, twinning and fracture is directly observable in order of occurrence. Either the "bottom" of the beam, a surface of pure tension may be observed or else the "side" of the beam in which the stress is tensile, zero, or compressive depending upon the region selected for view.

The structures with flake graphite exhibit comparatively little flow because of the sharp stress concentrations of the graphite flakes. Indeed a good share of the elongation exhibited by the materials containing flake graphite is made up of microcracks rather than of plastic flow.

The behavior of complex matrices is also of interest. When both ferrite and pearlite are present, local yielding occurs in the ferrite to a considerable extent before any plastic deformation of the pearlite is encountered.

As a further illustration of the close correlation of mechanical properties with structure the fracture of a hypereutectoid steel with carbide in the grain boundaries furnishes a classic example. The question has often been asked as to whether a completely continuous network is necessary to result in brittle fracture. The correlation of carbide distribution with ductility is quite evident from Figure 6.

2. Wear and abrasion.

Any engineer occupied with the problem of melting is often dismayed in viewing the large amount of intricately machined parts to be returned to the liquid state. The average automobile engine when scrapped for remelting has lost less than a percent of its weight when new. It is scrap because of wear at a few critical locations. Almost all properly designed machine parts fail by wear rather than breakage. The correlation of wear or abrasion resistance with metal structure is therefore of major importance.

There are many types of wear and abrasion, even in the same part such as an automobile tappet. Two engines of slightly different design will call for a difference in metal structure for optimum service. For the illustrations of this survey two principal types of wear and two of abrasion will be discussed.

Wear is considered here as the loss of metal under conditions in which no abrasive is introduced deliberately. The two cases are:

A. Lubricated wear wherein the lubricant may however attain boundary conditions and metal to metal contact is obtained. Example - automotive tappets.

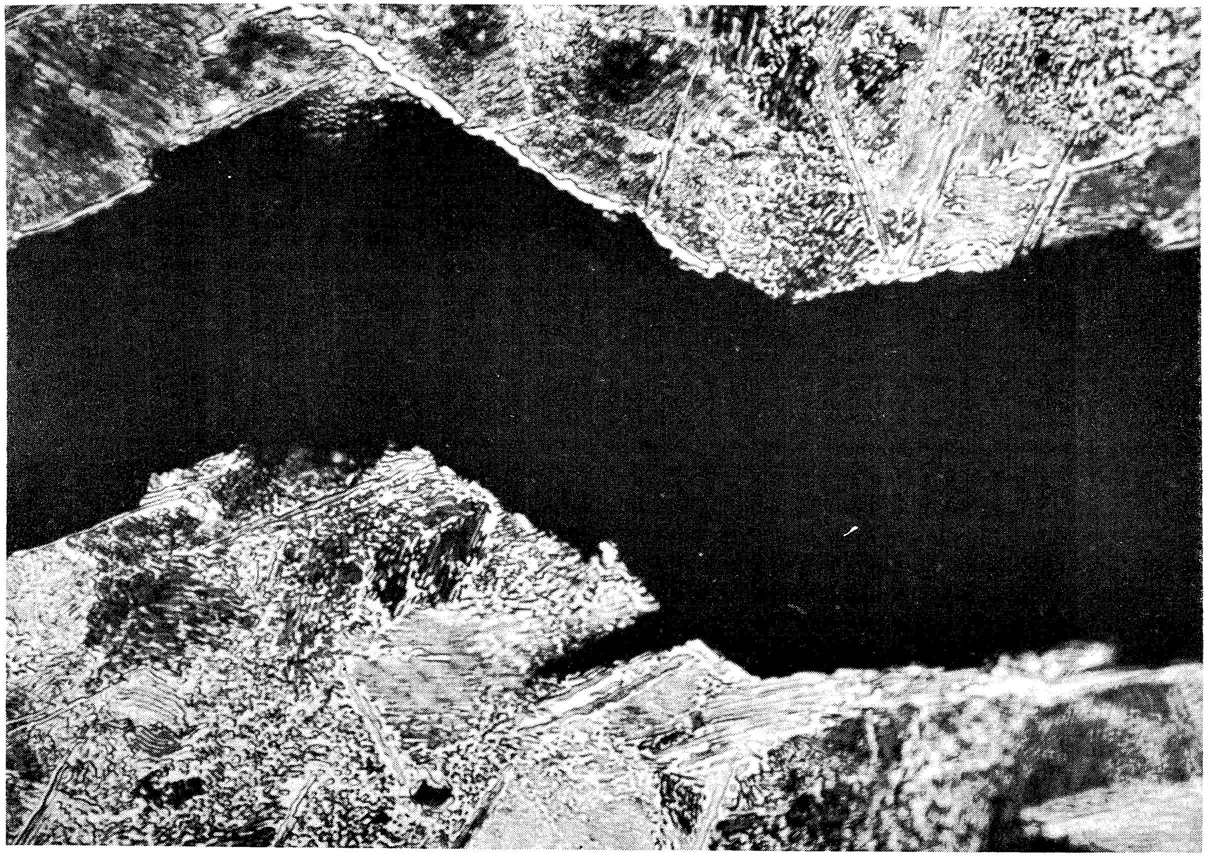


Figure 6. Microbend Stressing of Hypereutectoid (1.5% C) Steel with Grain Boundary Carbide (500X, Nital Etch)

B. Unlubricated wear. Example - railroad car wheel.

Abrasion is defined as metal loss under conditions in which an abrasion is handled deliberately as in grinding or conveying of minerals and ceramics. The two cases to be discussed are:

(a) Wet abrasion

(b) Dry abrasion.

These conditions may now be considered in order beginning with wear.

Lubricated Wear

The interaction of camshaft and tappet (valve lifter) is one of the most interesting cases in the automotive engine and is illustrated in Figure 7.(3) Almost every conceivable combination of alloys has been tried in these parts. Surface stresses are of the order of 100,000 psi and rubbing velocities are approximately 15 ft/sec at 4500 rpm. While this is commonly considered to be a case of lubricated wear, boundary conditions really exist in the splash system of the crankcase.

Two types of failure are encountered, corrosion fatigue at low rpm (1200) and scuffing at high rpm (4000). The fatigue mechanism is quite complex. The deleterious effect of certain additives in the oil accelerates failure markedly, indicating a corrosion fatigue mechanism. This portion of the problem is solved by the use of a hardened mottled iron of the following approximate analysis:

%C	%Mn	%P	%S	%Si	%Ni	%Cu	%Mo
3.3	0.7	0.20 max	0.20 max	2.0	0.5	1.0	0.4

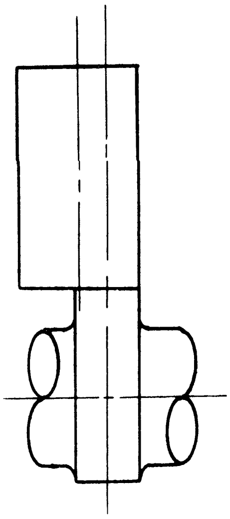


Figure 7. Interaction of Camshaft and Tappet in V-8 Engine

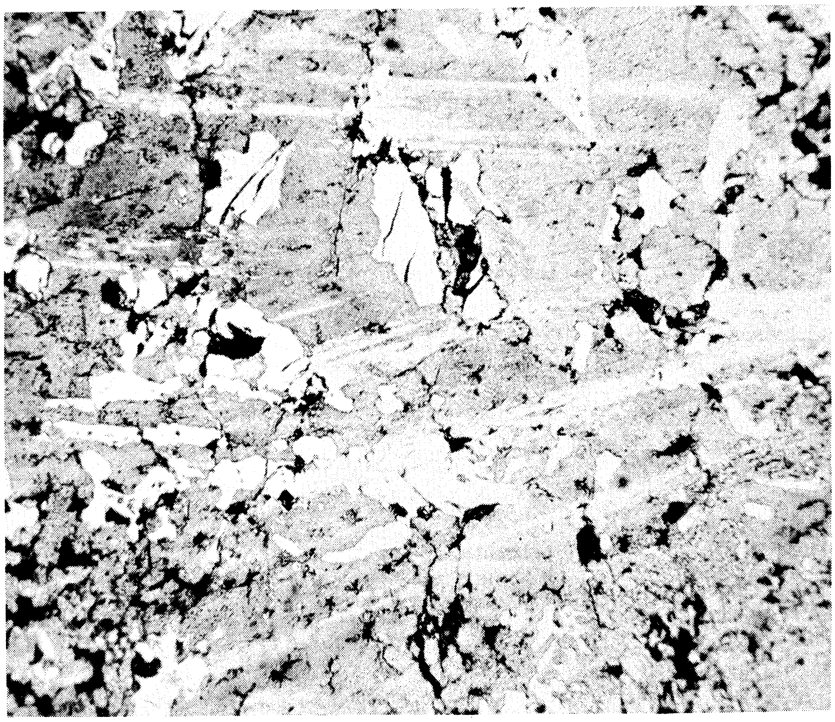


Figure 8. Layers of Scuffed Metal (Martensitic) Welded on Tappet During Service (100X, 2% Nital Etch). (Note cracked carbides as well.)

The other type of failure, scuffing or galling, is caused by the welding together of cam and tappet surfaces as a result of the intimate contact and frictional heat at high speeds. Figure 8 illustrates this welded on layer in the case of a tappet. This specimen was prepared merely by cleaning the worn surface and etching lightly with 2% nital. In Figures 9A,B, a cross section of a scuffed region of the tappet (and the mating cam) shows in order from the surface: A layer of scuffed metal, a fresh austenite martensite layer, then the characteristic tappet structure. The original tappet structure is produced by austenitizing at 1550°F for one hour, oil quenching and then tempering at 360°F for two hours. This results in a <u>tempered</u> austenite martensite matrix with the massive carbides and graphite of the as-cast mottled structure largely unaffected. The <u>fresh</u> austenite martensite layer must therefore have been produced as a result of friction.

The valuable indication of transient service temperatures given by the structure of the heated layer is of wide general interest. In many other wear applications where the overall gross temperature gives no indication of the mechanism of failure the structure at the failed surface provides an explanation. In this case, although the oil temperature and the average temperatures of the mating parts remain below 400°F, the transformed structure indicates local heating at above 1500°F.

As a result of extensive testing a structural specification(4) has been developed, Figure 10, to indicate the required distribution of massive carbide and graphite for optimum performance. This provides a balance of wear resistant carbide and of graphite pockets for boundary lubrication.

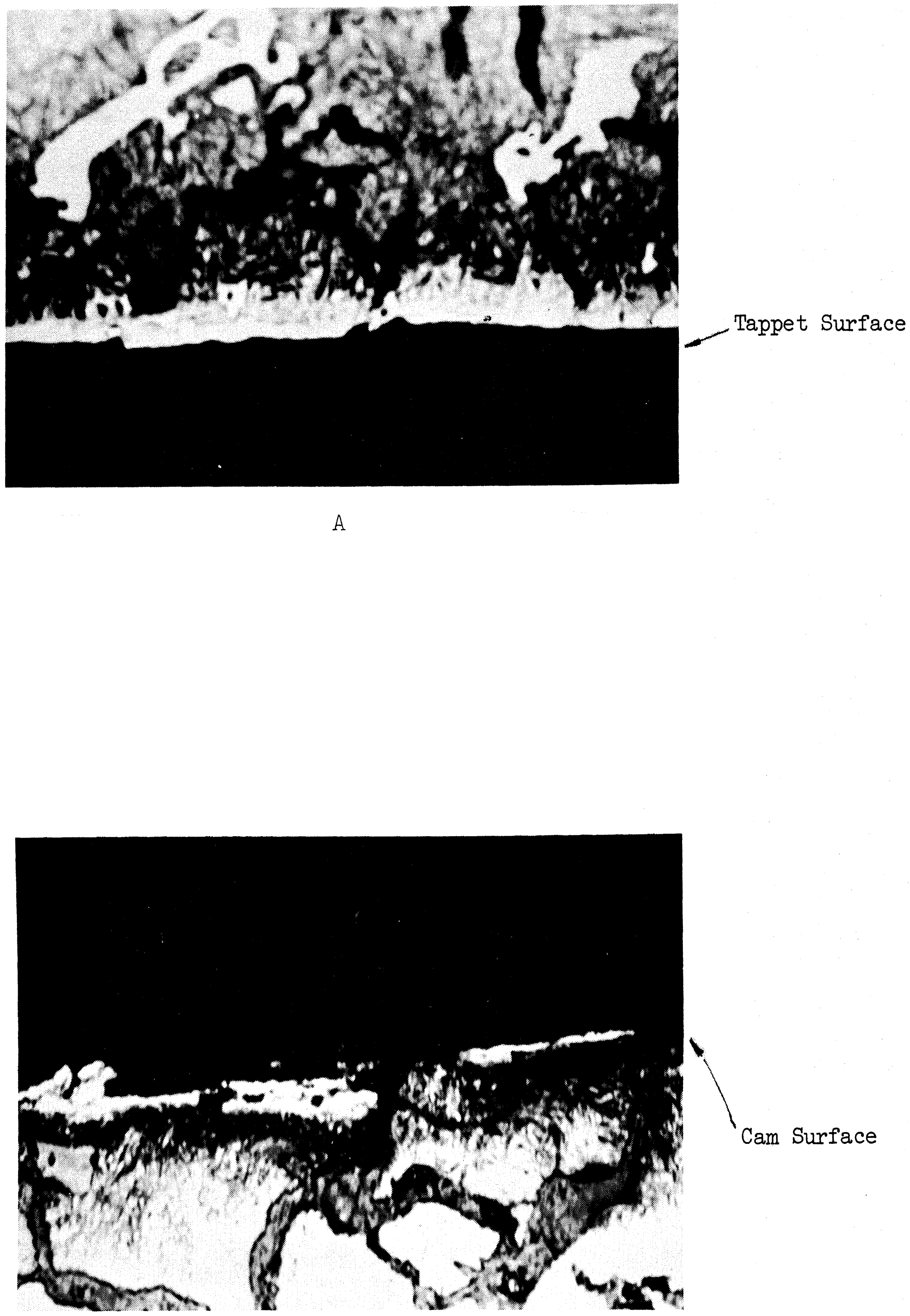


Figure 9. Cross Section of Tappet with Welded-On Metal (top) and Mating Cam (bottom)

(Note fresh martensite layer and tempered structure at depth. 1000X, Nital etch.)

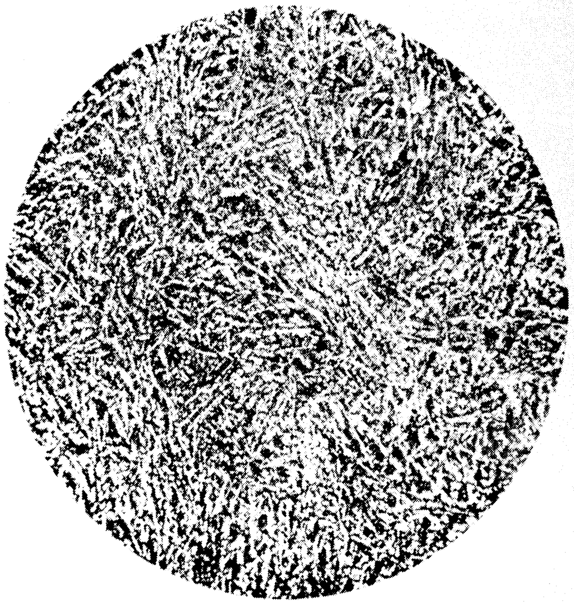


Figure 10. Structural Specification for Hydraulic Tappets (Mottled Iron with Controlled Carbide Distribution) 50X, Nital Etch.

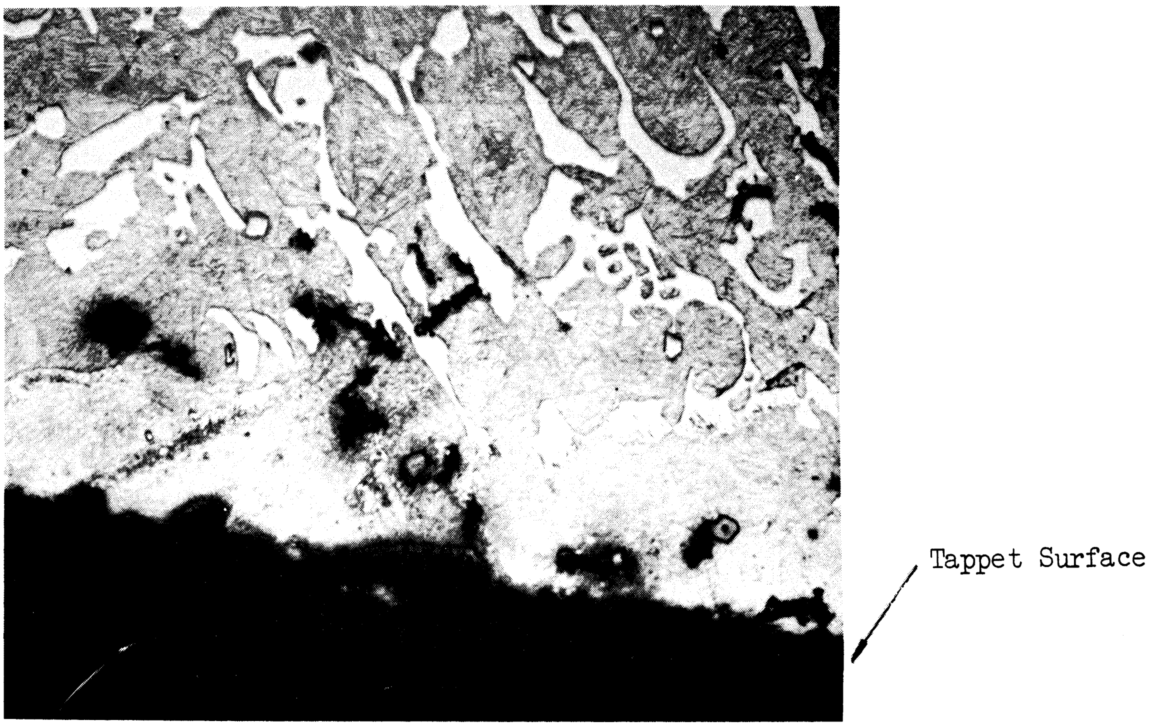


Figure 11. Decarburized Tappet Structure

As an example of variables which can be introduced during processing, the tappet structure of Figure 11 is of interest. Material of this type exhibited poor service performance although made from the same heats as satisfactory material. It will be noted that the massive carbides do not persist to the surface but stop short by several thousandths of an inch. Also in place of the graphite, pores* are encountered.

This softer and different structure leads to rapid scuffing. Once initiated, the rough welded structure leads to failure even though the proper structure is encountered beneath the surface.

The inferior structure, lacking in massive carbides, is caused by partial decarburization during heat treatment. It is remedied by control of furnace atmosphere and removal of sufficient stock during final grinding after heat treatment.

Unlubricated Wear

A long established application of major importance to the cast metals industry is the railroad car wheel. Here, of course, there is no attempt at lubrication and the surface stresses are high enough to cause flow in some materials. In addition to the mechanical problems, the wheel is heated intermittently by friction during brake shoe application.

For many years the standard freight car wheel material has been chilled cast iron of the following analysis:

%C	%Mn	%P	%S	%Si
3.5	0.6	0.3	0.1	0.5

In addition to control of chemical analysis, a white iron (graphite free) tread structure to a depth of 1/2 inch is required. The remainder of the rim and the plate and hub are soft gray iron. The hub is therefore quite machineable and the plate possesses a small but important amount of ductility. The white iron tread is produced by chilling as illustrated in Figure 12.

With the advent of higher speeds in freight service, increased thermal checking of the massive carbides was encountered because of the greater severity of braking. In Figure 13 a typical cross section of a worn chilled iron tread is exhibited. The original structure was massive carbide, spheroidized carbide and ferrite produced by very slow cooling, after casting, at a rate of about 10°F/hr. It is evident that considerate fragmentation of the carbides has taken place as a result of the thermal and mechanical stresses in severe service.

Several groups of materials were tested in a program directed toward improved service. (A) Structures containing graphite, (B) Ductile, graphite free structures (1.5% carbon and 0.75% carbon steel).

Graphitic Structures

From examination of the worn chilled wheel it was evident that the massive carbide led to a network of thermal checks and therefore should be eliminated. The two methods available were (1) conversion of carbide to graphite either by control of as-cast structures or by subsequent heat treatment, and (2) reduction in carbon content. Method 1 involved no change in processing facilities and was therefore attempted first. Also because of the voluminous literature indicating the beneficial effects of graphite in wear applications, the outlook was quite promising.

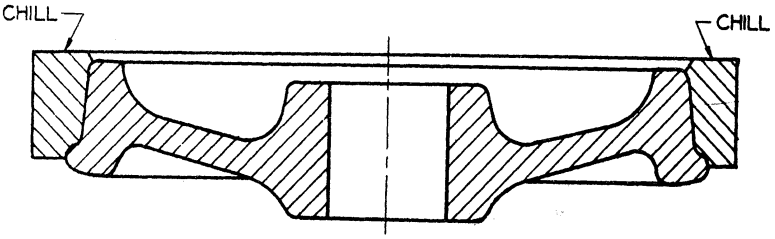


Figure 12. Cross Section of Chilled Iron Car Wheel Mold

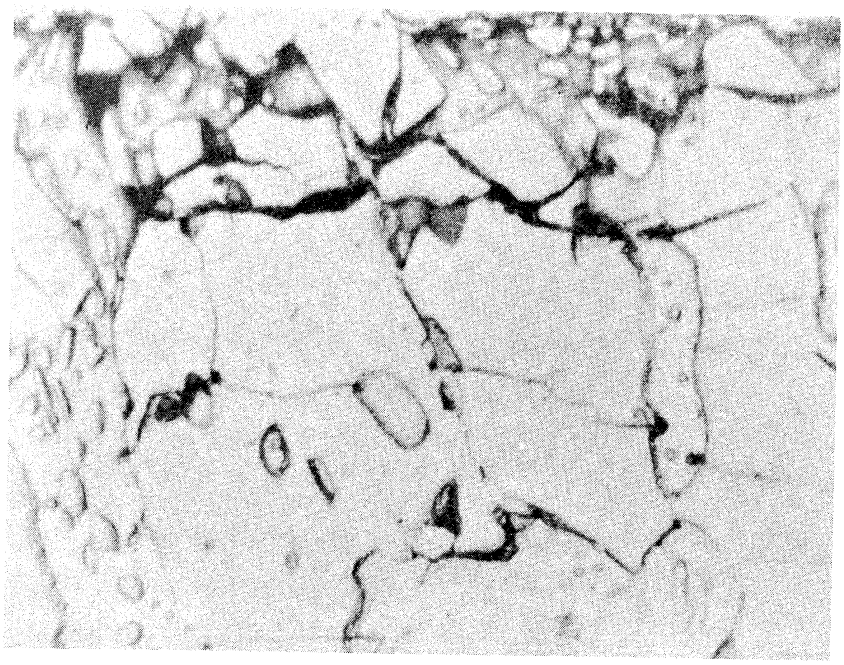


Figure 13. Cross Section of Tread Surface of Chilled Iron Car Wheel After Severe Service

The simplest method appeared to be to cast a gray iron wheel, eliminating the tread chiller. A modest (0.10% Si) silicon addition was made to the ladle to provide random graphite distribution. To minimize heat treatment expense, wheels were shaken out of the sand while in the austenitic range and subjected to a timed water quench at the tread. After removal from the quench the wheels equalized at 500-600°F providing adequate tempering of the martensitic structure produced in quenching. In this way samples at the same Brinell hardness (400) as the original white iron wheel were obtained. It should be pointed out that the structure, however, was quite different (tempered martensite and graphite compared to massive carbide and ferrite).

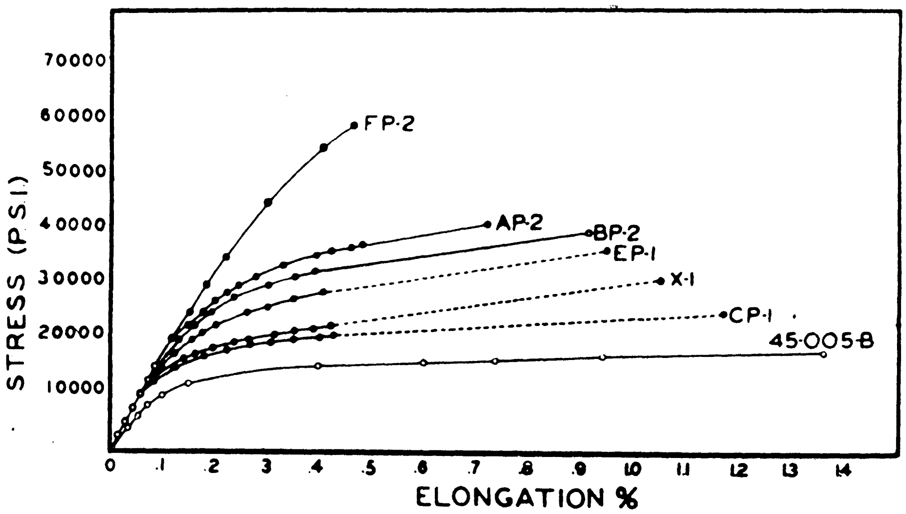
Specimens of the quenched and tempered gray iron were tested in a machine in which two cylinders were run against each other at the same stresses as encountered in service. One of the cylinders was typical rail steel, the other the experimental wheel material. These tests were very encouraging indicating a wear rate only 1/3 that of the chilled iron under similar circumstances. Tensile tests of the heat treated gray iron plate section indicated a strength approximately double that of the standard plate section. Despite this greater strength, quenched wheels failed castastrophically when braked in a test machine.

The reasons for this failure of a stronger structure form an interesting digression indicating first the often dominant importance of plastic strain compared to strength and secondly the changes in residual stress which can accompany a change in structure.

The stress strain curves of specimens cut from wheels of different manufacture are illustrated in Figure 14. While the ferritic matrix of the standard wheel possessed the lowest strength it also exhibited the greatest elongation. Now, when a brakeshoe is applied to the rim the temperature can be raised to 700-1000°F. The rim therefore expands, producing radial tension in the cold plate section. Strain measurements indicate that at least 0.5% elongation is required in the plate region. The tempered martensite of the quenched wheel (strong but low elongation) failed but the more plastic ferrite did not.

The residual stresses from heat treatment were a second factor. Before the quenching operation, the temperature of the hub and adjacent plate regions was approximately 1800°F when the rim was 1450°F. This differential was caused by the slower cooling rate of the more massive hub section. At this point, however, there was no residual stress (elastic strain) because the wheel was hot and plastic. The rim was then quenched for one minute exaggerating the thermal gradient still further. After quenching the rim was approximately 600°F, the hub and plate approximately 1200°F. There was still no appreciable residual stress since the hot and plastic hub section flowed as required. Upon cooling however the contraction of any element of the hot hub section was far greater than of the rim. The hub therefore tended to pull away from the rim leading to high residual tensile stress in a radial direction (over 40,000 psi). This residual stress, coupled with the low elongation led to early failure in the braking test.

This portion of the problem was solved by cooling the hub region with an airjet in the mold <u>before</u> the casting was removed for quenching.



Reference No.	Chemical Analysis, per cent TC	CC	GC	Mn	P	S	Si	BHN.	Heat Treatment
FP2	3.51	1.03	2.48	0.55	0.28	0.10	0.72	321	Quenched and tempered
AP2	3.48	0.84	2.64	0.54	0.27	0.10	0.77	194	Air cool
BP2	3.46	0.82	2.64	0.49	0.27	0.10	0.60	187	Mold cool
EP1	3.48	0.81	2.67	0.58	0.29	0.11	0.87	165	Mold cool, higher Si
X1	3.49	0.60	2.89	0.47	0.29	0.11	0.60	130	Cooled 10° F./hr.
CP1	3.48	0.44	3.04	0.55	0.30	0.13	0.72	124	
45-005B	3.51	0.40	3.11	0.61	0.07	0.08	1.05	103	

Figure 14. Stress-Strain Curves of Cast Irons of Different Matrix As Shown by Combined Carbon (C.C.)

The subsequent cooling of the tread resembled a shrink fit of a hot ring in a cold shaft and led to radial compression (25,000 psi). Also the entire wheel was rolled and rotated in a special quenching tank rather than quenching only the tread. The resulting microstructures are indicated in Figure 15. The objective - a safe component with a quenched and tempered martensitic gray iron structure at the rim - was attained in this manner.

Before proceeding with production adequate service tests under controlled conditions were performed. It is quite interesting that despite the favorable wear test machine indications, the wear rate was three times as high as the standard chilled wheel. In other words, service performance was inversely proportional to test machine data. Examination of worn surfaces indicated that the high stress concentrations around graphite flakes led to breaking out of material in these regions.

To remedy this condition, wheels were made with a nodular form of graphite in place of the flake type by malleableizing the standard chilled iron wheel. Material of this type also wore severely in service because the stresses were high enough to cause flow in the vicinity of the graphite. Consequently the graphite was pressed and stretched into layers which flaked off, Figure 16.

These experiments with graphitic materials led to the conclusion that the stresses were high enough to cause flow and fracture of the material adjacent to the flake. The alternative in eliminating the brittle massive carbide network was a change in composition, since above 2% carbon the as-cast massive carbides cannot be completely dissolved in any heat treatment in the solid state. Wheels were produced at 1.5% carbon using conventional greensand practice(5) and at 0.7% carbon employing permanent graphite molds(6).

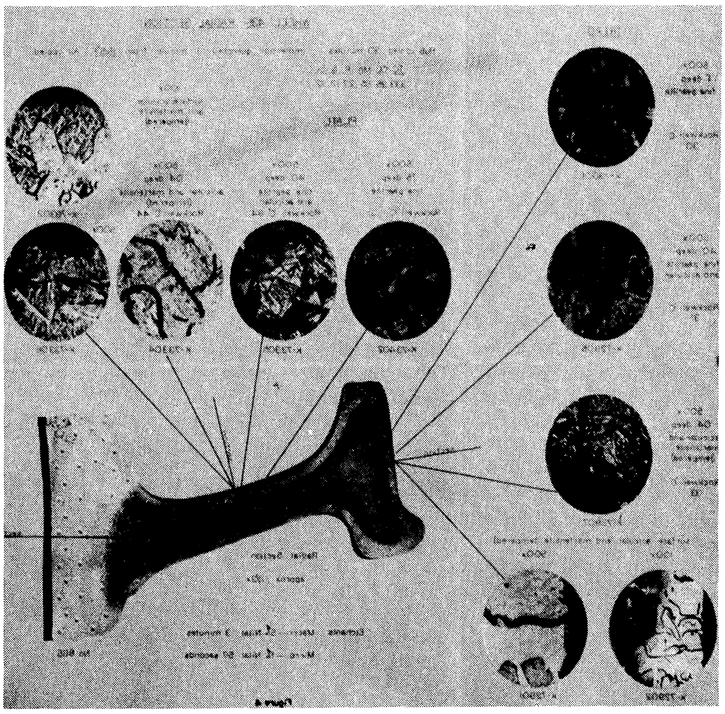


Figure 15. Microstructures of Quenched Gray Iron Car Wheel

Figure 16. Spalling of Railroad Car Wheel Tread Associated with Flake Graphite Aggregates. (1000X, Nital Etch)

Both of these structures exhibit excellent wear resistance.

One final comment regarding the effect of service conditions upon structure is of interest.

It has been found unnecessary to harden these steel wheels by a quenching and tempering operation for two reasons. The brake shoe action heats the outer layers to the austenite region and then (following a short brake application) the mass quench from the body of the wheel produces a martensitic surface layer. This effect is illustrated in Figure 17 and borne out by the microhardness readings for a wheel which was originally pearlitic. The second reason is a corollary of the first - any heat treated structure will be altered by the braking conditions. After prolonged braking for example, the mass quench of the balance of the wheel is not fast and a fine pearlite is often noted at the tread.

Abrasion

Under abrasive service conditions the part is required to withstand the action of foreign particles such as sand, rock, or clay which are introduced deliberately into the equipment as in grinding or conveying. Typical parts are ball mill liners and balls, sand slinger blades and grinding rolls.

Just as in the case of wear resistance it is found that there is no material which provides superior performance in all uses. The important variables in different services are:

Mechanical properties of the abrasive-hardness, toughness, etc.

Grinding stresses - Is the abrasive compressed under high stresses as in grinding or merely conveyed? Are impact stresses involved? The vehicle of the abrasive whether water, air or other agent is also of importance.

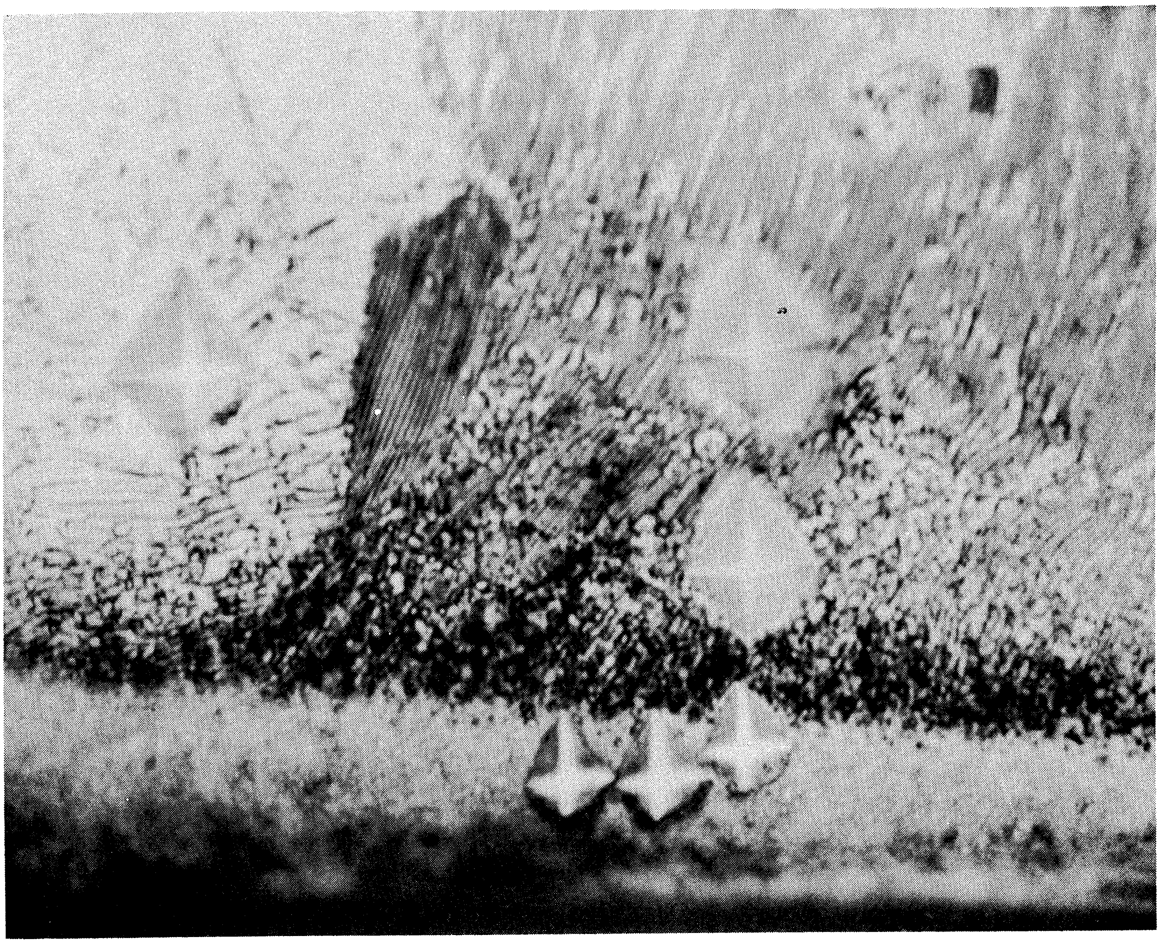


Figure 17. Martensitic Surface Produced in a 0.8% Carbon Steel Wheel by Brake Shoe Action
(Note microhardness impressions made with constant [25 g.] load.)

Despite the wide variety of conditions listed, a great many operations involve grinding at moderate pressures with quartz as the major abrasive. An abrasion test has been developed,(7) based on these conditions in which two specimens of the type shown in Figure 18 are rotated slowly on a copper track under a load of 100 lbs. The track is surrounded by an annular trough containing a slurry of quartz sand of standardized grain size and shape. One of the specimens is a standard of 1020 steel. The weight loss of both standard and unknown after an hour test is determined. The abrasion factor "A.F." of the material is determined as:

$$\frac{\text{weight loss of unknown}}{\text{weight loss of standard}}$$

This test provides good correlation with actual service performance in grinding.(6)

Some of the more interesting aspects of the data involve the dependence of the abrasion factor upon structure. In reviewing these data it is simpler to consider the abrasion factors of different steels first and then progress to the white and gray irons and the cemented carbides.

The different typical steel microstructures exhibit the following wet sand abrasion factors:

Structure	Type of Steel	BHN	Factor
Ferrite	Armco iron	90	1.40
Ferrite and coarse pearlite	SAE 1020 Annealed	170	1.00 standard
Pearlite	0.85% C steel Annealed	220	0.85
	Air cooled	350	0.75
Bainite	0.85% C steel isothermally transformed	512	0.75

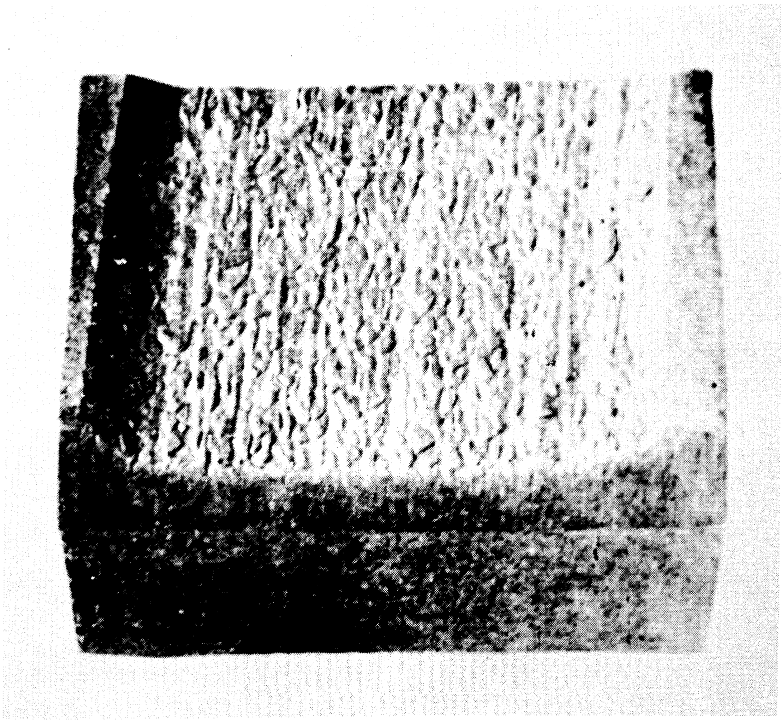


Figure 18. Abrasion Test Specimen After Testing

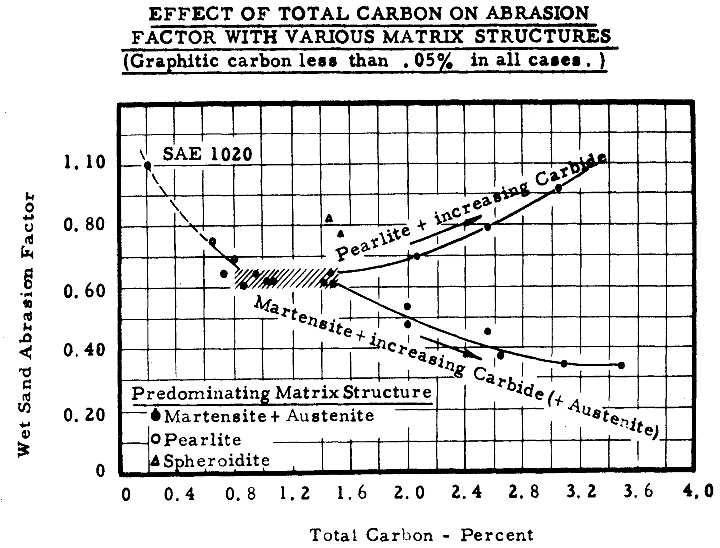


Figure 19. Effect of Massive Carbide Upon Abrasion Resistance of Different Matrices

Structure	Type of Steel	BHN	Factor
Martensite	0.85% C steel	715	0.60
Austenite	12% Mn, 1.1% C steel Water quenched from 1900°F	200	0.80

Perhaps the most interesting point is the relatively poor correlation with hardness, a criterion which is widely used. The superior performance of martensite is expected but it is surprising to encounter an intermediate factor for Hadfields manganese steel. A good share of the reputation of this latter material depends upon its great toughness. Many components such as gyratory crusher shells require this resistance to impact which is reflected in greater service life. Materials with better abrasion resistance crack and break rather than wearing out in these severe applications.

Now as either massive carbide or graphite is added rather unexpected changes in abrasion factor take place. The effect of massive carbide, Figure 19, may be considered first. In the case of pearlitic materials the addition of massive carbide increases the rate of wear (increased abrasion factor). Under these test conditions a chilled white iron exhibits poorer wear resistance than a pearlitic steel. On the other hand as massive carbide is added to martensite the rate of wear decreases.

Examination of worn structures indicates that when the hard carbide is supported by a soft matrix (pearlite), the matrix wears away and then appreciable amounts of carbide crack away rather than wearing off, leading to a poor abrasion factor. When the carbide is supported by a hard matrix (martensite) the cracking does not occur and the combination exhibits excellent wear resistance.

It should be noted carefully that the above results are obtained with quartz as an abrasive. When a softer abrasive is involved such as coal, limestone, or feldspar, the pearlitic chilled iron is superior to pearlite although not as satisfactory as martensitic white iron.

In the case of cemented carbides, the hard carbide constitutes a major portion of the surface and it is held by a tough bond. Apparently the combination of high carbide volume and extreme hardness avoids the harmful wearing away of the matrix obtained in white iron.

In other materials, the role of graphite is of great importance. Pearlitic gray cast iron has an abrasion factor of the order of 1.20. In this case the graphite flakes provide regions for rapid attack by the abrasive and the intervening material is then broken down more easily. Even in the martensite plus carbide structures a small amount of graphite has a noticeable effect. For example the presence of 1.0% graphitic carbon changes the factor from 0.30 to 0.40. This is a complex effect since a lesser amount of carbide is associated with the reduced graphite.

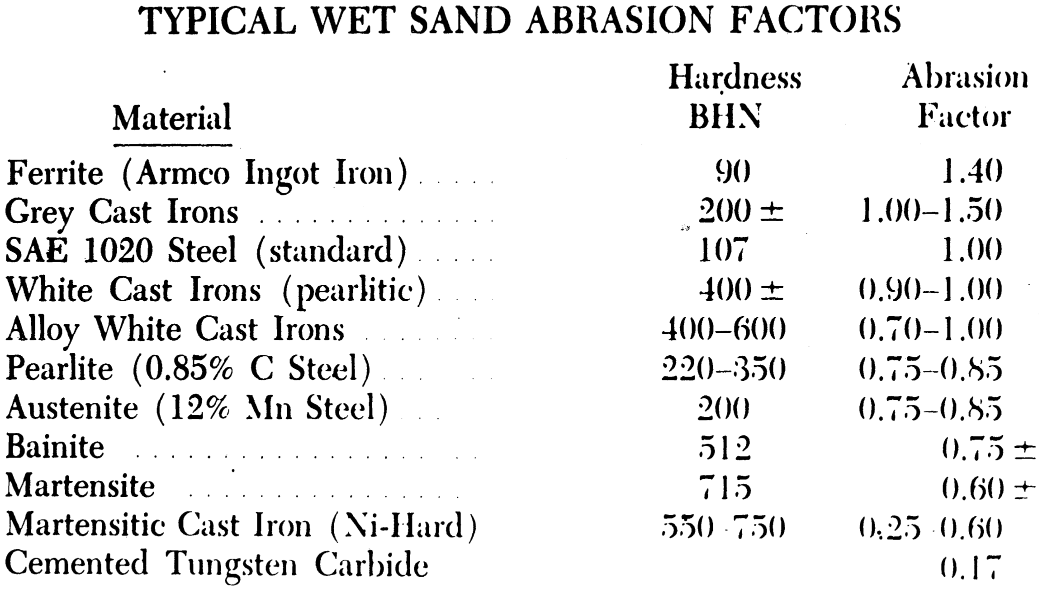
A summary of abrasion factors is given in Figure 20.(7)

Heat and Corrosion

Because of the length of the preceding discussion only a few examples in the field of heat resistant alloys will be described in order to illustrate the somewhat different type of correlation of heat resistance with structure. Some of the important features which affect the performance are:

Temperature

Variation in temperature rate of the variation and temperature limits



TYPICAL WET SAND ABRASION FACTORS

Material	Hardness BHN	Abrasion Factor
Ferrite (Armco Ingot Iron)	90	1.40
Grey Cast Irons	200 ±	1.00–1.50
SAE 1020 Steel (standard)	107	1.00
White Cast Irons (pearlitic)	400 ±	0.90–1.00
Alloy White Cast Irons	400–600	0.70–1.00
Pearlite (0.85% C Steel)	220–350	0.75–0.85
Austenite (12% Mn Steel)	200	0.75–0.85
Bainite	512	0.75 ±
Martensite	715	0.60 ±
Martensitic Cast Iron (Ni-Hard)	550–750	0.25–0.60
Cemented Tungsten Carbide		0.17

Figure 20. Summary of Abrasion Factors

External stresses

Thermal stresses

Atmosphere

In general, different components require peak performance ranging from seconds-as in rockets-to hours as in aircraft turbine blades-to decades as in steam turbines. Also the rate of heating of the part varies by several orders of magnitude.

Several examples of parts exposed to thermal shock as contrasted with longer term behavior may be selected now as illustrations.

Thermal Shock

One example of thermal shock has already received consideration - the application of a brake shoe to a car wheel tread. In this case the effects of heat such as cracking are developed by the thermal stresses resulting from differential expansion and phase transformation. The mechanical stress is negligible. Similar forces are encountered in automotive and other "friction" brakes and clutch plates. Interesting parallels are obtained in pig molds and glass molds which are also exposed to thermal shock. In all of these cases it is noteworthy that the tensile strength of the part is of negligible importance. One of the most successful materials has been gray cast iron with a high flake graphite content. Under similar service conditions, as in a pig mold, a more ductile material such as steel will warp out of shape. In contrast, the graphitic zones of the iron provide many tiny regions for allowing plastic and elastic deformation at high stresses without forcing the backing material to distort.

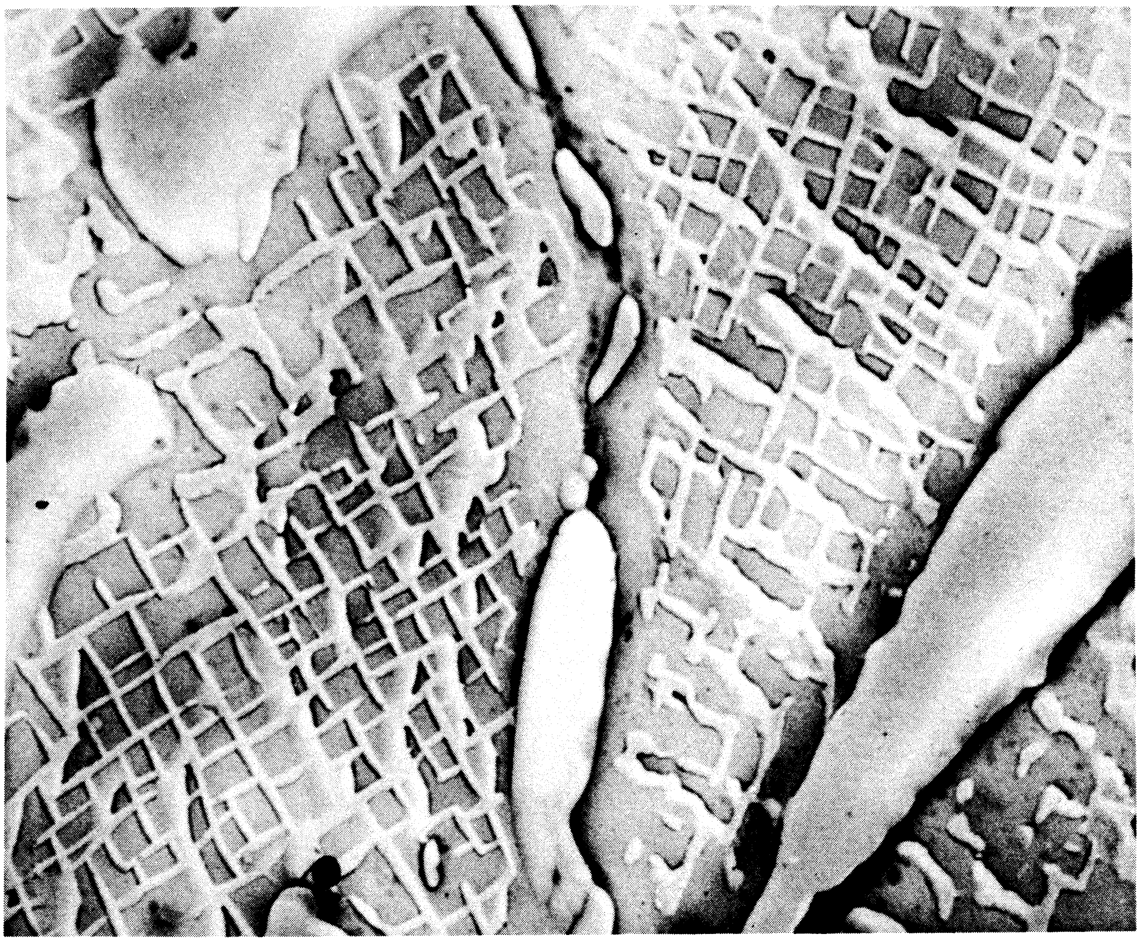


Figure 21. Ni_3Al (γ') Phase in Cast Nickel Base Heat Resistant Alloy (Cubic Network).
(Coarse particles are borides.)

Long Term Heat Resistance

Three important characteristics of long term service at elevated temperature are oxidation, creep and gradual alteration of metal structure. These effects are quite well known and have been investigated for many years.

The correlation of strength and creep rate at elevated temperatures with metal structure is not as predictable as, for example, the mechanical properties at ambient temperature. The mechanism of flow and fracture can be quite different at elevated temperatures. Better understanding of the character of the different heat resisting structures is now being obtained via the electron microscope and an interesting example may be cited.

For a long time puzzling structures were encountered in the nickel base alloys containing chromium, aluminum and titanium and boron. Under the light microscope these alloys apparently consisted of a homogeneous matrix with some gross borides.

Very high stress rupture strength of the order of 50,000 psi - 100 hours - 1500°F was encountered.

By the application of electron microscopy and X-ray diffraction techniques it was shown that a fine precipitate, the cubic phase in Figure 21, was present in the strong alloys of this type. Other research requiring the electron microscope directed toward the role of boron and zirconium, has indicated that these elements prevent deleterious carbide precipitation in the grain boundaries thereby avoiding microcracking and improving life.

Conclusions

Illustrations of the important variables to be considered in developing the best component for a particular application have been given.

An attempt has been made to show that unless all of these variables are evaluated, the wanton substitution of new materials can only lead to severe engineering errors of judgment. Conversely by thorough control of all variables not only can maximum performance be obtained from present engineering materials but the lines of research leading to new materials can be formulated.

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