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Wear Tests on Grinding Balls

BY T. E. NORMAN,* JUNIOR MEMBER AIME AND C. M. LOEB, JR., MEMBER AIME
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THE use of ball, rod and tube mills for grinding ore, cement and other materials has grown so rapidly during the past forty years that the world's annual consumption of ferrous grinding media for these mills is now estimated to be between one half million and one million tons per year. Ferrous grinding balls constitute the major portion of this tonnage. Obviously they represent sufficient value to justify thorough studies of the factor sgoverning their performance.

The selection of grinding balls is governed principally by: 1. Quality (wear resistance, impact resistance, soundness, and the like). 2. Sources of supply and delivered cost. 3. Grinding characteristics or efficiency in the ball mill. This paper deals principally with the quality of ferrous grinding balls. In the study of these factors certain data relative to the fundamental nature of ball wear in ball mills have been obtained. These data are also presented and discussed briefly.

THE DEVELOPMENT OF A SUITABLE WEAR TEST

A study of the fundamental factors governing the quality of grinding balls has been hampered seriously by the fact that a competent test has, in the past, involved the purchase of several hundred tons of balls of a specific type which were then run in one or more ball mills for a period ranging from several months to several years' duration. Often, during the period of test, it became necessary to change operating conditions or the character of the ore fed to the test mill with the result that the rate of ball consumption changed and the test figures became of little value. Under such circumstances, progress in the development of better grinding balls, has been necessarily slow.

Economic factors and variations in the quality of balls produced by different sources of supply generally make it necessary for each mill operator to determine for himself the most suitable type of balls for his mills. In our own ball mill grinding operations at Climax, Colo., we were faced with this problem. After we had run a few large scale wear tests at considerable expense we decided to investigate the possibilities of a small scale wear test which would be capable of testing numerous types of balls within a relatively short time.

The most important requirement of any test is, of course, that it give results which can be used to predict accurately the wear in full scale operations. It was known that Ellis and his associates[1,2] had developed a method of testing grinding balls by small scale tests run at the Ontario Research Foundation. Ellis' method of testing was used as a starting point in our investigations. In the course of our tests a number of modifications of the original method were found to be desirable so that, by an evolutionary procedure, a method of small scale

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* Metallurgical Engineer and Vice President, respectively, Climax Molybdenum Co., Denver, Colo. and New York City, N. Y.

[1] References are at the end of the paper.

testing has been developed which we believe makes possible an accurate estimation of the wear in full scale operations.

Our first small scale tests were run at the Colorado School of Mines State Experimental Plant in Golden, Colo. These were run in a Marcy ball mill approximately 3 ft id by 2 ft long, lined with ship-lap steel liners and equipped with a discharge grate which could be adjusted by means of diaphragm rings to discharge the ground pulp at various levels. The discharge could also be sealed for batch grinding tests. Fig 1 illustrates the arrangement used for the test when operating on open circuit grinding with a continuous feed and discharge. This arrangement was used for most of our preliminary tests though in a few cases it was found desirable to run a series of batch tests for the study of certain variables. Abrasives used in the tests were crushed Climax ore, a river sand very similar in abrasive characteristics to Climax ore, commercially pure crushed feldspar and a relatively pure type of crushed calcite. The balls tested were, in most cases, nominally 3 in. in diam.

Our preliminary tests differed from Ellis' method principally in the matter of dimensions. We used balls 3 in. in diam in a mill 3 ft in diam where Ellis, in most of his tests, used balls 1 in. in diam in a mill 1 ft in diam or smaller.

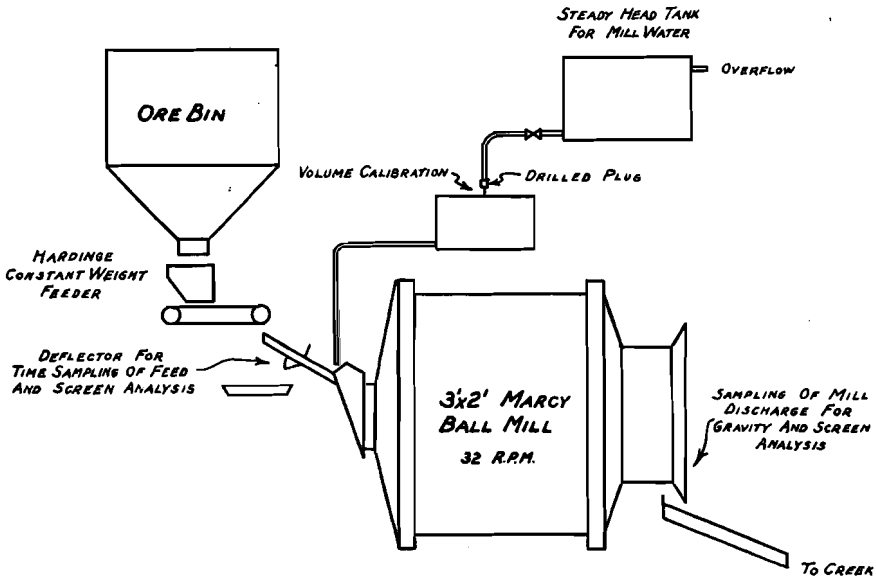

FIGURE 1

FLOW SHEET—WEAR TESTS AT GOLDEN

Our tests in the 3-ft mill were found to be useful for preliminary testing or for the study of certain fundamental factors affecting ball wear. Usually the order of merit of a series of balls could be quite well established in such tests. The test was found, however, to have certain limitations. For instance, the impact conditions in the 3 ft mill did not duplicate those in our large 9 ft diam mills at Climax. Also, the spread in relative wear resistance between a good and a poor type of ball was generally different from that obtained in our larger mills at Climax, or in the mills at other mining operations.

Ellis[1] has demonstrated that the character of the abrasive has a marked influence

on the relative wear resistance of various types of balls. This was confirmed in our preliminary tests. Ordinarily the hard abrasives such as quartz give a relatively small spread while the softer abrasives, such as feldspar and calcite, tend to produce a relatively large spread between the wear resistance of a good and a poor type of ball.

Because of the foregoing limitations of the tests in the 3 ft mill, a new testing technique was developed whereby many types of balls could be tested on a small scale in a commercial mill without seriously interfering with its regular operation. Results of such tests, when comparisons have been available, show excellent agreement with large scale tests made in the same mills where only one composition was used for the entire ball charge.

Detailed Procedure for Running Wear Tests in Commercial Mills

The technique used in running our wear tests, in its final stage of evolution, was as follows:

1. A series of groups of balls was selected with the balls in each group representing steel or iron of a specific type and treatment. A "group" usually consisted of from 5 to 15 balls. Our tests have indicated that if all the balls in any group are similar each ball will show, within the limits of experimental error, exactly the same weight loss per unit of area. There was very little advantage to be gained therefore from the use of large groups. One group of balls in each series was of the type used as a standard for comparison.

2. The balls in each group were marked with a distinctive mark, such as one or two notches or drilled holes or a combination of a notch and a drilled hole. Where two notches or drilled holes and notches were used on a ball, they were placed at definite angular distances from each other on the ball surface. Generally the marks were about ¼ in. deep with the holes ¼ in. diam and the notches 1/16 or ⅛ in. wide by 1 in. long. The notches were cut with a small abrasive cut-off wheel.

Comparative tests have indicated that the one or two notches or holes placed in these test balls produced no measurable difference in rate of wear except in cases where spalling occurred at the edge of the notches. Where spalling did occur, it was generally of such a nature that the weight loss due to this spalling could be estimated and the necessary corrections made to determine the weight loss caused by wear alone.

3. After marking, the surface defects such as scaling and decarburization were removed from the test balls by a "wear-in" in a small ball mill for a sufficient time to remove metal to a depth of at least 0.040 in. below the original surface of the ball.

4. Where the groups of test balls were to be run in a large mill along with the regular charge from which it would be difficult to recover all the test balls, it was found necessary to adjust the weight (after the wear-in) of each ball in a group to an identical value. This was done by grinding on an abrasive grinding wheel. By having all balls in a group of equal weight at the beginning of the wear test it was unnecessary to recover all the balls in the group from the mill when the test was complete.

5. All the balls were weighed carefully both in air and while suspended in water containing a wetting agent. From these data the density, volume and surface area of each ball were calculated by assuming that the ratio of volume to surface area was equal to that of a perfect sphere.

6. The mill in which the wear test was to be run was selected and the entire series of test balls charged at once. They were allowed to run in this mill, along with the regular charge of balls under normal operating conditions, for a sufficient period of time to establish a reliable wear factor. In commercial mills the test balls were generally run for a sufficient length of time to wear off a layer of metal about ⅛ in. thick

from their surface. The mill was then stopped and the marked test balls were sorted out from the rest of the charge. Sorting was accomplished by dumping the entire charge of balls on the floor, or, preferably in large mills, by having two or three men pick the marked balls from the surface of the ball charge inside the mill while it was slowly rotated 180° with a crane and rope.

The time for shutdown and recovery of balls from a test mill was generally chosen so that it would coincide with the time the mill was to be shut down for relining or other repairs. By doing this the wear test did not interfere with normal operations of the ball mill. We did not attempt to find 100 pct of the test balls. Generally, however, from 60 to 80 pct of them were found without difficulty within about 2 hr. During the search period a close watch was kept for test balls which had broken or spalled during the test.

7. The test balls were sorted, cleaned and weighed and their weight loss per unit of surface area was calculated. This figure was compared to the loss per unit of area on the standard balls included in the test. From this comparison an "abrasion factor" or relative rate of wear was calculated. For instance on a typical test the standard balls lost 116.0 g per 100 sq cm of original surface area. The balls in "group 1" showed an average loss of 128.7 g per 100 sq cm. The standard ball was always nominally assigned an abrasion factor of 100. The abrasion factor (relative rate of wear) of the balls in group 1 was, therefore, $\frac{128.7}{116.0} \times 100 = 111.0$. In this paper all abrasion factors are given to the nearest whole number.

All abrasion factors listed in this paper have been obtained by the foregoing procedure. In all cases our standard for comparison was a group of martensitic forged steel balls containing 0.75 to 0.88 pct carbon and 0.20 to 0.30 pct molybdenum. These standard balls had been made in regular commercial practice under carefully controlled conditions and were found to be very uniform in quality.

In studying the abrasion factors given in this review it should be clearly realized that they represent relative rates of wear. Balls with an abrasion factor higher than 100 wear away faster and are, therefore, poorer than the standard, while balls with an abrasion factor of less than 100 wear more slowly and are, therefore, superior to the standard.

The abrasion factor represents the relative rate of wear of that portion of the ball which was worn away during the test. If the ball is homogeneous from surface to center the abrasion factor should be representative of relative wear resistance of the entire ball. In some cases, however, the ball may be less wear resistant at its center than at its surface. When this condition exists, allowances must be made in evaluating the relative wear resistance of the entire ball. Generally, however, the correction necessary is very slight. For instance, if a steel ball 3 in. in diam is fully hardened to a depth of 1 in. below its surface, then the weight of hardened steel in the ball is 96.3 pct of the total weight with the unhardened core representing only 3.7 pct of the total weight. Under such circumstances the correction necessary for the more rapid wear rate of this core will probably be less than 1 pct when applied to the average wear rate of the entire ball.

Surface decarburization to a depth of 0.030 in. may increase the rate of wear of a ball 3 in. in diam by a greater amount than a soft core 1 in. in diam. Such a layer represents approximately 6 pct of the total weight of the ball. We estimate that such a zone of decarburization will generally shorten the life of a 3 in. ball by 1 to 2 pct. On smaller balls the influence of decarburization would be still greater.

The data and conclusions presented in this paper are supported by wear tests run

over a 7 yr period on over 200 metallurgical classifications of steel and iron balls. A total of 94 wear tests was run to study numerous variables under a wide variety of operating conditions. The entire mass of data collected, if presented in this paper, would increase its length excessively and tend to obscure many of the more important findings which we feel the investigation has brought forth. The data presented in this paper will, therefore, be confined principally to illustrative examples rather than to a complete compilation of all results.

Rates of Wear and Limits of Accuracy

Once the surface of a test ball has been suitably prepared, the determination of an accurate abrasion factor is merely a matter of running the test ball along with a standard for a sufficient length of time to wear off an accurately measurable amount of metal. In our tests we attempted to wear off a sufficient weight of metal on each test so that our limit of experimental error in weighing was less than 1 pct. In the 3 ft diam test mill at Golden, Colo., we found that a 24 hr test, using a continuous feed of crushed Climax ore, washed river sand or washed river pea gravel would wear 15 to 30 g from a ball 3 in. in diam. For a group of 5 to 15 balls, this was sufficient to obtain the desired degree of accuracy.

When running tests in which it was necessary to add the abrasive and water in batches instead of continuously we usually ran each test for a period of 6 hr with the abrasive being changed every 2 hr. Two or more of these 6-hr tests were generally run in order to obtain a check on our results.

In the tests in commercial mills the average period of the wear test was from one to two weeks which in most cases wore off 75 to 400 g per ball. This was ample to establish wear factors with a high degree of accuracy. In one case, however, in which we ran a test in a mill grinding cement clinker the rate of wear was so low that only 4.5 g were worn off each 3 in. standard ball after a 222 hr run. While the limit of experimental error on this test was relatively high, a compensating factor was found in the fact that the spread in wear resistance between the good and poor types of balls was so great that there was no doubt about the relative merits of the various types tested.

Table 1 gives the actual rates of wear obtained on our standard balls when run in ten tests representing a rather wide variety of operating conditions. From these values of wear rates per unit of area, the rate at which the balls decrease in diameter and their useful life period have been calculated for each condition. This calculation assumes that mill operating conditions remain constant and that the wear on each ball continues to be in direct proportion to its surface area for its entire life. The life of individual balls in a mill is of particular interest when large scale wear tests are planned on one or more types of balls. General practice on such tests is to start adding the test balls to the mills daily in the quantity needed to maintain the ball charge at a desired level. When the operator is satisfied that the balls formerly used in the mill are substantially all worn out, and the test balls have worn in sufficiently to form an equilibrium ball charge, he then starts to keep an accurate record of the weight of test balls added to the mill. It may be seen from Table 1 that this method of testing can develop into a long, tedious process because of the fact that it requires months and in some cases years to replace the former charge of balls with the test balls.

The rate at which individual balls wear will tend to be faster in mills of large diameter than in mills of small diameter. Theoretically the wear rate of an individual ball in a charge will increase as the 0.6 power of the mill diameter. This general trend for the balls to wear faster in the larger diameter mills is observable from the data in Table 1. An accurate experimental

TABLE 1—*Wear Rates on Standard Martensitic Forged Steel Balls in Various Mills*

Company	Location	Abrasive	Mill Diameter (Feet)	Ball Makeup Diameter (Inches)	Wear per 100 Sq Cm per 24 Hrs (Grams)	Loss in Diameter per 24 Hr (Inches)	Approximate* Life (Days)
Climax Molybdenum Co.	Climax, Colo.	Mo ore	9	100 pct—3 in.	22.7	0.0228	99
Climax Molybdenum Co.	Climax, Colo.	Mo ore	9	50 pct—3 in. 50 pct—2 in.	17.1	0.0172	131 on 3 in. 73 on 2 in.
Climax Molybdenum Co.	Climax, Colo.	Mo ore	6	100 pct—3 in.	13.3	0.0134	168
Homestake Mining Co.	Lead, S. Dak.	Gold ore	5	100 pct—2 in.	9.0	0.0090	139
Phelps-Dodge Corp.	Ajo, Ariz.	Copper ore	6½	100 pct—3 in.	8.6	0.0086	262
Miami Copper Co.	Miami, Ariz.	Copper ore	8	100 pct—3 in.	10.4	0.0105	214
Colo. Portland Cement	Portland, Colo.	Dry cement clinker	8	4 in. and smaller	0.24	0.00024	13,500 on 4 in.
Colo. School of Mines	Golden, Colo.	River sand	3	3 in.	8.3	0.0083	271†
Colo. School of Mines	Golden, Colo.	Feldspar	3	3 in.	3.7	0.0037	608†
Colo. School of Mines	Golden, Colo.	Calcite	3	3 in.	0.31	0.00031	7260†

* The "life" of a ball is calculated here as the time required to wear it from its original diameter down to 0.75 in. diameter.
† This life is on a charge consisting entirely of 3 in. balls. If the charge had been an equilibrium charge containing balls graduated from 3 in. diam down to 0.75 in. then the wear rate would have been less and the life longer due to the greater total surface area of such a charge.

determination of this 0.6 power rule is, however, rather difficult because of the numerous other variables which generally enter the picture when we change from a mill of one diameter to that of another diameter.

FUNDAMENTAL FACTORS GOVERNING BALL WEAR IN A MILL

In the development of a suitable testing technique, one of the first things we had to determine was the basis on which we could compare the wear of balls which varied in diameter or weight. Davis[3] had stated that balls wore in direct proportion to their weight (or cube of their diameter). Ellis[1] in most of his tests based his wear rates on weight loss per unit of surface area, that is, he assumed that balls wore in direct proportion to the square of their diameter. Bond[4] states that the balls in his tests wore as the 2.29 power of their diameter. Since both Davis' and Bond's methods of determining the proportionality of ball wear were of an indirect nature, we felt that further evidence on this subject should be obtained by more direct methods of observation. Groups of balls were, therefore, prepared which were metallurgically and chemically similar, the only variable being their diameter. These groups were run on various tests in a number of mills. It was found that the balls in these groups wore in direct proportion to their surface area, that is, in proportion to the square of their diameter. An exception to this surface area rule was found in the case where a few balls 4 to 5 in. in diam were run in a charge which consisted principally of balls 3 in. in diam and smaller. It was found that under such conditions the abnormally large balls tended to segregate to the outside of the mill charge where they would naturally absorb a greater than average amount of energy and, therefore, wore somewhat faster than was called for by the surface area law.

The mills in which these tests were run have varied from 3 to 9 ft in diam. Mill speeds ranged from 65 to 78 pct of critical while pulp densities and pulp levels varied sufficiently to produce a wide variation in the degree of impact to which the balls were subjected. In spite of these wide variations in operating conditions, we have been unable to find any deviation from this surface area law for ball wear except for the case mentioned where the large balls segregated to the outside of the mill.

Since, in the absence of size segregation, grinding balls in a mill will tend to wear in direct proportion to their surface area, the wear per unit of area will be the same on metallurgically and chemically similar balls even though these balls vary in size. Data from a number of our tests which confirm this observation are given in Table 2. It will be noted that within the limits of experimental error, for any given test, the wear per unit of area on balls of various diameters is practically identical.

Since grinding balls tend to wear in direct proportion to their surface area, it also follows that they will tend to lose diameter at a constant rate. This has been very nicely confirmed by Prentice's[5] investigations. Garms and Stevens[6] show a further confirmation of this in Fig 2 of their paper.

Davis[3] based his conclusion that balls wear in proportion to their weight on the screen analysis of a number of ball charges. Prentice[5] has compiled more recent data on the screen analysis of a number of ball charges. His compilation, and unpublished data from the screen analysis of ball charges in our Climax mills, tend to confirm the surface area theory of ball wear.

The nature of ball wear in a ball mill hae been the object of much discussion ever sincs Davis[3] published his original paper on thie subject. It is suggested that our techniqur of wear testing can be used to yield furthes experimental data on this problem. Our tests indicate that the wear in a ball

TABLE 2—*Wear Rates of Balls of Various Diameters in Several Tests**

a. Annealed, Forged Steel, Plain Carbon Balls in 3-ft Diam Mill at Golden. Results from one 24-hr Test in River Sand and one 24-hr Test in Climax Ore

Nominal Diameter (Inches)	Actual Area (Sq Cm)	Grams Lost per 100 Sq Cm	
		Sand	Climax Ore
3	178.1	11.0	10.1
2	78.6	10.6	9.8

b. Martensitic Forged Steel (Standard) Balls in a 5-ft Diam Mill at Homestake Mining Co. Results from 239-hr Test in Partially Ground Homestake Ore

Nominal Diameter (Inches)	Actual Area (Sq Cm)	Grams Lost per 100 Sq Cm
3	170.0	89.8
3	176.6	89.1
2½	124.8	90.3

c. Soft Pearlitic Forged Steel Balls (277 Brinell) in a 5-ft Diam Mill at Homestake Mining Co. Results from a 239-hr Test in Partially Ground Homestake Ore

3	164.9	110.1
3½	224.5	109.7

d. Soft Pearlitic Forged Steel Balls (277 Brinell) in a 6½-ft Diam Mill at Phelps Dodge Corp., Ajo, Ariz. Results from a 168-hr Test in Ajo Ore

2¾	151.4	94.8
3¼	209.0	95.3

e. Martensitic Forged Steel (Standard) Balls in a 3-ft Diam Mill at Golden. Results from one 24-hr Test in River Sand and one 24-hr Test in Climax Ore

Nominal Diameter (Inches)	Actual Area (Sq Cm)	Grams Lost per 100 Sq Cm	
		Sand	Climax Ore
3	163.0	8.28	8.43
2½	113.9	8.31	8.30

f. Martensitic Forged Steel (Standard) Balls in a 9-ft Diam Mill at Climax, Colo. Results from one 162-hr Test in Climax Ore

Nominal Diameter (Inches)	Actual Area (Sq Cm)	Grams Lost per 100 Sq Cm
3	175.5	116.3
3	170.0	115.8

* The results given represent averages. A total of five to twenty balls of each type was run in each test

charge tends to be uniformly distributed over the surface so that the wear on any one ball is proportional to its surface area. It would seem to follow that the energy induced by rotation of the mill and the grinding effect are similarly distributed.

The Mechanism of Wear

Our wear tests lead us to believe that wear may be classified in all cases as occurring by two mechanisms. One is by the removal of oxide films or other chemical coatings which form on the freshly exposed metallic surface of the wearing part. When wear occurs by this mechanism, the chemical composition of the metal is the dominating factor. A reduction of wear under these conditions can be most readily accomplished by selecting a metal or alloy which forms a hard and adherent oxide film such as that obtained on high chromium alloys.

The other classification of wear involves the removal of the surface of the part as metallic particles. When wear occurs by this mechanism, we believe the controlling factors governing rate of wear are determined by the distribution and characteristics of the micro-constituents in the metal or alloy. In the case of grinding balls, operating in mills of commercial size, our tests indicate that most of the wear occurs by the removal of metallic particles since the microstructure of all balls tested has been the dominant factor in the determination of their wear resistance. For instance, we have found that balls of the same analysis but of different microstructure will generally show a corresponding difference in wear resistance. On the other hand, balls of widely different alloy content but with practically the same microstructure will show relatively small differences in wear resistance.

Ellis[2] has found, under the conditions existing in his laboratory testing of grinding balls, that wear caused by the removal of oxide films was a dominating factor. His tests were run in small jar mills on balls 1 in. in diam. Under these conditions the addition of chromium to his steel or iron composition was found to be very effective in reducing ball wear. We suspect that when wear in grinding balls occurs primarily by the removal of oxide films, the forces causing abrasion are unusually mild. Where larger balls are used in the larger test mills, or in mills of commercial size, the metallic particles worn from balls during a wet grinding operation can generally be removed from the ground pulp by gravity or magnetic concentration, though a complete separation is difficult. Probably the finer particles are rapidly oxidized, so quantitative determinations of metallic iron in the ground pulp may be misleading. These ground pulps, when allowed to stand, will often generate surprisingly large volumes of hydrogen, indicating the reduction of hydrogen ions by the metallic iron. This hydrogen evolution is the basis of one quantitative method of determining the amount of metallic iron in these pulps.

We believe that the oxide films play only a minor part in determining the wear of grinding balls in most ball mills. In acid or corrosive pulps, or where small balls are used in mills of small diameter, the influence of oxide films on the balls may become an important consideration. The microstructure of the steel or iron balls may also have a definite influence on the formation of the oxide films. Metallographists are all familiar with the fact that pearlite etches more rapidly than martensite when exposed to oxidizing acids. We have indications that a similar condition exists during the formation of oxide films on the freshly abraded surfaces of grinding balls. For instance, on a series of batch tests in the 3 ft diam mill at Golden, using crushed Climax ore as the abrasive, when the mill atmosphere was changed from air to a pure oxygen atmosphere, a group of pearlitic steel balls showed a 39 pct increase in rate of wear while the standard martensitic

balls showed only a 19 pct increase in rate of wear. On the other hand, when we attempted to reduce the rate of oxidation of the balls by operating in an air atmosphere with an alkaline pulp, the pearlitic balls showed a 10.7 pct decrease in rate of wear while the martensitic balls showed only a 7.4 pct decrease. The martensitic steel was, therefore, less affected by changes in oxidizing conditions than the pearlitic steel. Since the oxygen in an air atmosphere apparently did have some influence on rate of wear, it is reasonable to expect that at least some reduction in rate of wear by oxidation may be achieved by making the steel martensitic.

The changes in rate of wear which we obtained by the use of an oxygen atmosphere or by making the pulp alkaline are not nearly so great as those obtained by Ellis[2] in his small jar mills. We believe the reason for this is that in our tests the wear by removal of oxide films did not represent nearly as great a proportion of the total as it did in Ellis' small laboratory mills.

Definition of Microstructural Classifications

Since the balls in our wear tests were studied with particular reference to their microstructure, a brief definition of the terms used to describe these microstructures is in order.

During the solidification of a medium or high carbon steel or of hypoeutectic compositions within the white iron range, the first constituent to solidify is austenite. Upon cooling, this austenite may transform to pearlite, bainite, or martensite with the product of transformation depending on the temperature at which the austenite transforms. The austenite and its transformation products are often referred to as the "matrix" of the steel or iron, and are, at times, so designated in this paper. During the cooling of the solidified austenite, pro-eutectoid carbides or ferrite may be rejected. Since these constituents are rejected around the austenite grains, they are referred to as grain boundary carbides or ferrite.

Spheroidized carbides, which occurred in several groups of balls which we studied, were produced by reheating operations after casting or forging. They existed in all cases as very small globular particles finely disseminated throughout the matrix of the steel.

Sulphides were observable and easily identified in several cast steels of high sulphur content. Where they occurred as envelopes or partial envelopes around the original austenite grains, they are classed as grain boundary sulphides. Where they occurred as globules within the original austenite grain boundaries they are classed as globular sulphides.

When ferrous alloys within the cast iron range of compositions solidify, there will form around or adjacent to the original austenite grains: carbides, which we shall designate as primary or massive carbides; graphite, which will be so designated; and steadite, an iron phosphorus eutectic. In one case, ledeburite, which is a eutectic of austenite or its transformation products and primary iron carbide, is mentioned.

Pearlite is the lamellar product resulting from transformation of austenite at temperatures from the Ae1 temperatures (approximately 1350°F (730°C) for most of the compositions studied) and about 1000°F (540°C). It will be further classified into coarse, medium and fine pearlite depending on the size and spacing of the lamellae. Bainite is the acicular product resulting from transformation of austenite at temperatures which are generally below 900°F (480°C) and above 450°F (230°C). For most of our compositions, the bainite was formed between 800 and 500°F (430–260°C). Substantial amounts of retained austenite generally were found along with the bainite. Martensite refers to the hard acicular product formed below the Ar″ temperature of the steel. This Ar″

temperature was within a range of 550 to 350°F (290–180°C) for most of the compositions which we studied. There were, however, a few compositions which contained a total alloy content sufficient to depress the Ar″ temperature to values near or below room temperature so that refrigeration was necessary to obtain appreciable transformation from austenite to martensite.

The similarity in appearance between martensite and low temperature bainite is such that we may, in a number of cases, have confused one with the other. On our more recent investigations we have attempted to distinguish between bainite and martensite by determining the temperatures at which the balls transformed with "Tempilstiks" and a magnet.

Spheroidite as described by Payson[7] has also been studied in a few of these wear tests. This structure was obtained in a few of the normalized high carbon, low alloy steels.

Wear Resistance of Steel of Various Microstructures

Microstructure seems to be the dominating factor insofar as the wear resistance of steel grinding balls is concerned. Structure of the matrix appears to be most important. Grain boundary carbides and undissolved spheroidized carbides have a minor, though by no means negligible, effect on wear resistance. The effect of massive carbides is variable and appears to depend to some extent on the character of the matrix. Grain boundary and massive carbides have a pronounced influence on the resistance shown by the balls to spalling and breakage under severe impact. Grain boundary ferrite is harmful to wear resistance.

Carbon content plays such a dominant part in determining the microstructure of a steel or iron that its influence will be discussed in this section on microstructure rather than in a later section on the influence of chemical composition on wear resistance.

The relative wear resistance (abrasion factors) of eleven of the more important types of steel and iron representing certain typical microstructures is listed in Table 3. The abrasion factors obtained under seven different operating conditions are given. The eleven analyses are listed in their approximate order of merit.

Generally, in the conduct of our wear tests, a wide variety of types was included in each test. The complete data from two of our more comprehensive tests are listed in Tables 4 and 5 for illustrative purposes. It is from such data as these that we have taken the selected data for Table 3.

In studying the influence of microstructure on wear resistance, our discussion can be conveniently divided into three parts, one dealing with a matrix structure made up of austenite, martensite, or bainite or a combination of these, and the second with a matrix structure of fine, medium or coarse pearlite. The third part deals with structures containing a matrix of spheroidal carbides in ferrite.

1. *Balls with a Matrix of Austenite, Martensite or Bainite*

A well known form of steel containing austenite is found in the 12 to 14 pct manganese, 1.0 to 1.3 pct carbon Hadfield manganese steel which has been reheated after casting to about 1900°F (1040°C) and water quenched. This steel represents a rather stable form of austenite which can be work hardened from its as-quenched hardness value of about 10 Rc to a maximum of 58 Rc. In our work on grinding balls the highest hardness observed on the work hardened surface of Hadfield manganese steel was 54 Rc. We have never been able to detect the transformation of this austenite to ferro-magnetic products (such as martensite) by work hardening of the surface. This applies to both balls and crusher parts. This finding is supported by the work of Goss[8] who concluded that no such products are formed from the work

TABLE 3—*Abrasion Factors of Typical Microstructures When Tested as 3-in. Grinding Balls in Various Mills*

	Conditions of Test						
Mill Location	Lead, S. D.	Golden, Colo.	Climax, Colo.	Climax, Colo.	Ajo, Ariz.	Golden, Colo.	Portland, Colo.
Mill Diameter (Feet)	5	3	6	9	6½	3	8
Mill Speed (rpm)	27	32	25	20	23.1	32	17.5
Pulp Density (pct Solids)	75	73	77	75	70	70	Dry
Discharge Level of Pulp	High	High	High	Low	High	High	Low
Duration of Test (Hours)	239	48	145	162	168	36	222
Type of Ore	Gold	River Sand	Molybdenum	Molybdenum	Copper	Feldspar	Cement Clinker
Principal Abrasives	Iron-Magnesium-Silicate	Quartz and Feldspar	Quartz and Feldspar	Quartz and Feldspar	Feldspar and Quartz	Albite and Orthoclase	Ca. Aluminate Ca. Silicate

Item No.	Microstructure	Hardness Bhn	Carbon Per Cent	Abrasion Factors						
				Lead, S. D.	Golden, Colo.	Climax, Colo.	Climax, Colo.	Ajo, Ariz.	Golden, Colo.	Portland, Colo.
1	Mart., Aust., primary Carb. (sand cast)	601	3.23	95	101	95		84	72	
2	Bainite or Martensite plus Austenite	512–627	0.90–1.01	96		95	96	90	77	
3	Martensite, some retained Aust. (Std.)	652–683	0.80–0.86	100	100	100	100	100	100	100
4	Mart., Aust., primary Carb. (chill cast)	637	3.27		106	104	Spalled			Broke
5	Fine high carbon Pearlite	364	1.01	104	107	110	110	128	244	
6	Fine eutectoid Pearlite	375	0.71	110	110	115	115	132	264	366
7	Austenite (Hadfield Mn Steel)	207	1.14	120	133	130	124	154	364	
8	Coarse Pearlite	269	0.70	123		134	127	158		
9	Fine Pearl., primary Carb. (chill cast)	475	3.20	128		138	Spalled	163		
10	Coarse Pearl, primary Carb. (chill cast)	444–460	2.70–3.20	139	160	154	Broke	175	247	
11	Coarse Pearl, primary Carb. (sand cast)	475	3.20		178	176				

Abbreviations: Mart. = Martensite.
Carb. = Carbide.
Aust. = Austenite.
Pearl = Pearlite.

TABLE 4—*Relative Rates of Wear of 3-in. Diameter Grinding Balls in a 6 × 6-ft. Mill at Climax, Colo. (May 1941)*

Item No.	No. of Balls	Heat Treatment	Microstructure	Hardness† Bhn	Analysis, Per Cent									Density, G. per cc	Abrasion Factor
					C	Mn	Cr	Mo	Ni	Cu	Si	S	P		
(a) Forged Steel															
1	5	Oil Quench from forge, T. 375°F.	Mart., Bain. (?), Aust.	627	1.01	0.44	1.06	0.21			0.34			7.77	95
2	6	Oil Quench from forge, T. 375°F.	Mart., Bain. (?), Aust.	578	1.03	1.32	1.06	0.22			0.40			7.80	97
3	12	Forged, reheated 1525°F., W.Q., T. 375°.	Mart., Spheroidized Carbide	683	1.01	0.44	1.06	0.21			0.34			7.81	97
4	7	Oil Quench from forge, T. 375°F.	Mart., Bain. (?), Aust.	683	0.75	0.45	0.42	0.26			0.65			7.75	98
5	15	Forged, reheated, W.Q. T. 300°F.	Martensite, austenite	652	0.86	0.59		0.29			0.26	0.029	0.011	7.81	100 Std.
6	12	Forged, reheated, O.Q. T. 375°F.	Mart., Bain., Aust.	652	0.75	0.45	0.42	0.26			0.65			7.78	100
7	10	Water quench from forge	Martensite	745	0.70	0.66					0.15			7.84	100
8	14	Forged, reheated, W.Q.	Martensite	668	0.71	0.63					0.22	0.033	0.013	7.82	101
9	15	Forged, reheated, O.Q.	Not observed	534	0.86	0.59		0.29			0.26	0.029	0.011	7.83	102
10	3	Delayed O.Q. from forge, T. 450°F.	Mart., Aust., G.B. Carbide	600	1.03	1.32	1.06	0.22			0.40			7.79	103
11	15	Forged, air cooled	Fine pearlite, G.B. Carbide	387	1.03	1.32	1.06	0.22			0.40			7.81	109
12	15	Forged, air cooled	Fine pearlite, G.B. Carbide	364	1.01	0.44	1.06	0.21			0.34			7.80	110
13	10	Oil quench from forge	Fine pearlite	370	0.75	0.60*					0.20*			7.85	110
14	7	Forged, oil quenched, T. 1050°F.	Tempered martensite	387	1.01	0.44	1.06	0.21			0.34			7.80	113
15	6	Forged, oil quenched, T. 1050°F.	Tempered martensite	402	1.03	1.32	1.06	0.22			0.40			7.78	113
16	15	Forged, air cooled	Fine pearlite	387	0.75	0.45	0.42	0.26			0.65			7.79	114
17	15	Oil quench from forge	Fine pearlite	375	0.71	0.63					0.22	0.033	0.013	7.83	115
18	14	Oil quench from forge	Fine pearlite, a little ferrite	375	0.70	0.66					0.15			7.82	116
19	8	Forged, oil quenched, T. 1050°F.	Tempered martensite	387	0.75	0.45	0.42	0.26			0.65			7.80	124
20	14	Oil quench from forge	Bainite, Martensite	408	0.46	1.74								7.83	124
21	10	Forged, air cooled	Not observed	340	0.52	1.45	0.85				0.19	0.042	0.026	7.83	126
22	15	Forged, air cooled	Pearlite	302	0.86	0.59					0.29	0.029	0.011	7.83	130
23	20	Forged, air cooled	Coarse Pearlite	286	0.70	0.88					0.27			7.80	133
24	15	Forged, air cooled	Coarse Pearlite	258	0.71	0.63					0.22	0.033	0.013	7.83	134
(b) Cast Steel															
25	8	Sand Cast, norm. 1800°F., T. 600°F.	Spheroid. Carb., T. Mart.	555	1.10	0.47	5.45	0.51			0.73	0.02*	0.04*	7.69	98
26	4	Sand Cast, norm. 1800°F., T. 600°F.	Spheroid. Carb., T. Mart.	600	0.85	0.48	5.88	0.47			0.70	0.02*	0.04*	7.63	100
27	6	Chill Cast, air cooled	Martensite, Austenite	512	0.84	1.14	2.61	0.43	1.51		0.47	0.02*	0.04*	7.72	101
28	4	Sand Cast, norm. 1800°F., T. 1000°F.	Spheroid. Carb., T. Mart.	555	0.85	0.48	5.88	0.47			0.70	0.02*	0.04*	7.61	103
29	8	Sand Cast, cooled in sand	Aust., Pearl., G.B. Carb.	375	1.10	0.47	5.45	0.51			0.73	0.02*	0.04*	7.68	104
30	9	Chill Cast, air cooled, T. 600°F.	Tempered Martensite	555	0.73	0.95	1.84	0.42	0.99		0.47	0.02*	0.04*	7.75	104

31	5	Sand Cast, norm. 1650°F., T. 600°F	Tempered Martensite	601	0.78	0.93	1.63	0.48	0.87		0.44	0.02*	0.04*	7.69	104
32	14	Chill Cast, air cooled	Fine pearlite, G.B. Carbide	468	1.36	0.93	1.68	0.39	0.98		0.55	0.02*	0.04*	7.71	104
33	13	Sand Cast, cooled in sand	Fine Pearlite	352	1.06	1.51	2.63	0.53			0.44	0.02	0.04	7.78	106
34	14	Sand Cast, cooled in sand	Fine Pearlite	341	1.06	2.02	3.05	0.26			0.42	0.05	0.01	7.83	107
35	4	Sand Cast, cooled in sand	Pearlite, G.B. Carbide	351	0.85	0.48	5.88	0.47			0.72	0.02*	0.04*	7.63	108
36	4	Sand Cast, cooled in sand, T. 1000°F	Pearlite, G.B. Carbide	341	0.85	0.48	5.88	0.47			0.70	0.02*	0.04*	7.62	108
37	14	Sand Cast, cooled in sand	Fine Pearlite, G.B. Carbide	388	1.29	1.03	1.60	0.42	0.99		0.41	0.03	0.06	7.77	109
38	7	Sand Cast, cooled in sand	Fine Pearlite	375	0.91	1.04	1.66	0.43	0.78		0.61	0.02	0.04	7.62	110
39	7	Sand Cast, cooled in sand	Fine Pearlite	364	0.86	1.04	1.66	0.43	0.78		0.61	0.02	0.04	7.67	110
40	7	Sand Cast, cooled in sand	Fine Pearlite	369	0.78	0.93	1.63	0.48	0.87		0.44	0.02*	0.04*	7.74	111
41	6	Sand Cast, ann. 1800°F., norm. 1650°F	Spherodite	351	0.86	1.04	1.66	0.43	0.78		0.61	0.02*	0.04*	7.64	113
42	8	Sand Cast, reheated 1900°F., W.Q	Austenite	200	1.14	12.38					0.54	0.02*	0.04*	7.72	130
			(c) Chill Cast Iron												
43	4	Cooled in air	Mart., Aust., massive Carb.	637	3.27	0.50*	1.50*		4.50*		0.50*			7.74	104
44	15	Cooled in air	Pearlite, massive Carbide	475	3.20*	0.40*	0.90*	0.25*			1.70*			7.51	138
45	10	Cooled in air	Pearlite, massive Carbide	460	2.75	0.75*					0.30*	0.15*	0.15*	7.57	153
46	13	Cooled in sand	Coarse Pearl., massive Carb.	477	3.60*	0.50*					0.55	0.10*	0.30*	7.58	154
47	7	Cooled in air	Pearlite, massive Carbide	444	2.70	0.21	0.02	0.02			0.22	0.16	0.12	7.59	163
			(d) Sand Cast White Iron and High Metalloid Steels												
48	7	Cooled in sand	Mart., Aust., massive Carb.	600	3.23	0.64	1.89		4.26		0.62	0.11	0.10	7.71	95
49	8	Cooled in sand, T. 400°F	Mart., Aust., massive Carb.	600	3.23	0.64	1.89		4.26		0.62	0.11	0.10	7.72	96
50	15	Cooled in sand	Pearlite, G.B. Sulphide	364	0.99	0.55	2.69	0.35			0.50	0.19	0.33	7.72	119
51	14	Cooled in sand	Pearl., G.B. Sulph. and Carb.	387	1.24	1.03	2.63	0.28			0.36	0.12	0.31	7.72	122
52	15	Cooled in sand	Pearl., mass. Carb., glob. Sulph.	401	1.53	1.68	2.56	0.54			0.47	0.16	0.32	7.71	127
53	15	Cooled in sand	Pearl., mass. Carb., glob. Sulph.	415	1.53	1.66	2.61	0.26			0.49	0.17	0.33	7.73	130
54	15	Cooled in sand	Pearl., G.B. Sulphide	331	1.02	0.50	0.19	0.57	1.04		0.42	0.17	0.30	7.75	130
55	14	Cooled in sand	Coarse Pearl., globular Sulph.	285	1.02	1.07					0.46	0.19	0.33	7.72	141
56	5	Cooled in sand	Pearl., G.B. Sulph. and Carb.	460	1.54	2.92	1.10				0.51	0.15	0.26	7.72	141
57	14	Cooled in sand	Fine, Pearl., massive Carb.	532	3.00	1.51	1.94		2.75		0.64	0.13	0.29	7.70	151
58	15	Cooled in sand	Pearlite, Steadite, mass. Carb.	477	3.00*	0.65*	0.80*	0.25*			0.90*	0.17*	0.40*	7.62	176
59	14	Cooled in sand	Pearl., Ledeburite, mass. Carb.	578	3.20*	0.70*	2.50*			2.50*	0.80*			7.69	182

* Approximate analysis.

† Hardness refers to the hardness of the metal actually removed by wear.

Abbreviations: W.Q. = Water Quenched; O.Q. = Oil Quenched; T. = Tempered; G.B. = Grain Boundary; Norm. = Normalized; Mart. = Martensite; Bain. = Bainite; Aust. = Austenite; Carb. = Carbide; Sulph. = Sulphide; Spheroid. = Spheroidized; Mass. = Massive; Glob. = Globular

TABLE 5—*Relative Rates of Wear of 3-in. Diameter Grinding Balls in 6½ × 15-ft. Mill at Phelps Dodge Corp., Ajo, Ariz. (November 1941)*

Item No.	No. of Balls	Heat Treatment	Microstructure	Hardness† (Bhn)	Analysis, Per Cent									Density, G per cc	Abrasion Factor
					C	Mn	Cr	Mo	Ni	Cu	Si	S	P		
				(a) Forged Steel											
1	5	Oil quench from forge, T. 375°F.	Mart., Bain., Aust.	627	1.01	0.44	1.06	0.21			0.34			7.77	90
2	6	Oil quench from forge, T. 375°F.	Mart., Bain., Aust.	578	1.03	1.32	1.06	0.22			0.40			7.80	92
3	15	Forged, reheated, W.Q., T. 300°F	Mart., Aust.	652	0.80	0.60		0.29			0.26			7.81	100 Std.
4	10	Oil quench from forge	Fine pearlite	370	0.75	0.60*					0.20*			7.85	131
5	14	Oil quench from forge	Fine pearl., a little ferrite	375	0.70	0.66					0.15			7.82	133
6	15	Forged, air cooled (2¾ in.)	Coarse pearlite	286	0.70	0.88					0.27			7.80	157
7	15	Forged, air cooled (3¼ in.)	Coarse pearlite	269	0.70	0.88					0.27			7.82	158
				(b) Cast Steel											
8	10	Chill cast, air cooled	Aust., Bain., trace of pearl.	364	0.90	1.68	2.85	0.41			0.58	0.02*	00.4*	7.75	94
9	5	Chill cast, air cooled	Aust., Bain., Pearl.	452	0.96	1.68	3.43	0.32			0.65	0.03*	0.04*	7.77	94
10	5	Chill cast, air cooled	Bain., Aust.	512	0.88	0.97	1.56	0.33	0.59		0.92	0.03*	0.04*	7.72	96
11	1	Chill cast, W.Q. ½ min. air cooled	Bain., Aust., globular Sulph.	555	1.00	1.21		0.30*			0.35*	0.06*	0.17*	7.76	97
12	1	Chill cast, W.Q. ½ min. air cooled	Bain., Aust., globular Sulph.	555	1.01	1.19		0.30*			0.35*	0.06*	0.17*	7.76	98
13	3	Chill cast, water quenched	Mart., Aust., G.B. Sulph.	627	0.95	0.90				0.30*	0.35*	0.06*	0.17*	7.69	98
14	3	Chill cast, water quenched	Mart., Aust., G.B. Sulph.	682	0.90	0.85				0.30*	0.35*	0.06*	0.17*	7.72	99
15	1	Chill cast, water quenched	Mart., Aust., G.B. Sulph.	601	1.00	1.21		0.30*			0.35*	0.06*	0.17*	7.72	100
16	2	Chill cast, water quenched	Mart., Aust., G.B. Sulph.	640	0.94	1.36		0.30*			0.35*	0.06*	0.17*	7.71	100
17	4	Chill cast, water quenched	Mart., Aust., G.B. Sulph.	682	0.78	0.75		0.30*		0.30*	0.35*	0.06*	0.17*	7.68	100
18	20	Chill cast, air cooled	Bain., Aust., Pearl.	582	0.79	0.92	1.32	0.27			0.47	0.05	0.13	7.62	104
19	8	Sand cast, norm. 1800°F., T. 600°F	Spheroid. Carb., T. Mart.	555	1.10	0.47	5.45	0.51			0.73	0.02*	0.04*	7.69	107
20	5	Chill cast, air cooled	Pearl., Mart., Aust.	534	1.03	1.36	2.00	0.30*		1.00*	0.35*	0.06*	0.17*	7.75	112
21	5	Chill cast, air cooled	Pearl., Mart., Aust.	535	1.03	1.35		0.30*		2.00*	0.35*	0.06*	0.17*	7.76	112
22	13	Chill cast, air cooled	Fine Pearl., G.B. Carbide	468	1.36	0.93	1.68	0.39	0.98		0.55	0.02*	0.04*	7.71	121
23	1	Chill cast, W.Q. ½ min. air cooled.	Bain., Mart., Aust., G.B. Sulphide	444	0.94	1.36		0.30*			0.35*	0.06*	0.17*	7.77	125
24	8	Sand cast, cooled in sand	Aust., Pearl., G.B. Carbide	375	1.10	0.47	5.45	0.51			0.73	0.02*	0.04*	7.68	126
25	13	Sand cast, cooled in sand	Fine Pearlite	352	1.06	1.51	2.63	0.53			0.44	0.02	0.04	7.78	128

TABLE 5—(*Continued*)

Item No.	No. of Balls	Heat Treatment	Microstructure	Hardness† (Bhn)	Analysis, Per Cent									Density, G per cc	Abrasion Factor
					C	Mn	Cr	Mo	Ni	Cu	Si	S	P		
26	7	Sand cast, cooled in sand.....	Fine Pearlite	364	0.86	1.04,	1.66	0.43	0.78		0.61	0.02*	0.04*	7.67	132
27	6	Sand cast, ann. 1800°F., norm. 1650°F.....	Spheroidite	351	0.86	1.04	1.66	0.43	0.78		0.61	0.02*	0.04*	7.64	135
28	1	Chill cast, W.Q. ½ min., air cooled.....	Pearl., Bain., G.B. Sulphide	363	0.92	0.92					0.35*	0.06*	0.17*	7.77	137
29	5	Chill cast, air cooled.....	Pearl., Mart., G.B. Carb., and Sulph.	401	1.02	1.16		0.30*		1.00*	0.35*	0.06*	0.17*	7.75	143
30	1	Chill cast, W.Q. ½ min. air cooled.....	Pearl., G.B. Sulphide	363	0.92	0.90				0.30*	0.35*	0.06*	0.17*	7.78	153
31	5	Chill cast, reheated 1900°F., W.Q.....	Austenite	207	1.15	12.50					0.60*	0.02*	0.04*	7.75	154
32	5	Chill cast, air cooled.....	Aust., G.B. Carbides	207	1.15	12.50					0.60*	0.02*	0.04*	7.74	155
			(c) Sand and Chill Cast Iron												
33	7	Sand cast, cooled in sand.....	Mart., Aust., Massive Carb.	601	3.23	0.64	1.89		4.26		0.62	0.11	0.10	7.71	84
34	8	Sand cast, cooled in sand, T. 400°F.....	Mart., Aust., Massive Carb.	601	3.23	0.64	1.89		4.26		0.62	0.11	0.10	7.72	87
35	15	Chill cast, air cooled.....	Pearl., Massive Carbide	512	3.20*	0.40*	0.90*	0.25*			1.70*			7.51	163
36	10	Chill cast, air cooled.....	Pearlite, massive Carbide	460	2.75	0.75					0.30*	0.16*	0.15*	7.57	168
37	10	Chill cast, air cooled.....	Pearlite, massive Carbide	444	3.00*	0.50*					0.60*	0.15*	0.25*	7.69	170
38	27	Chill cast, air cooled.....	Pearlite, massive Carbide	469	2.75*	0.75*					0.30*	0.16*	0.15*	7.57	173
39	15	Chill cast, air cooled.....	Pearlite, massive Carbide	486	2.75*	0.75*					0.30*	0.16*	0.15*	7.55	181
40	7	Chill cast, air cooled.....	Pearlite, massive Carbide	444	2.70	0.21	0.02	0.02			0.22	0.16	0.12	7.59	185

* Approximate analysis.
† Hardness refers to the hardness of the metal actually removed by wear.
Abbreviations: W.Q. = Water Quenched; T. = Tempered; G.B. = Grain Boundary; Mart. = Martensite; Bain. = Bainite; Aust. = Austenite; Pearl. = Pearlite; Sulph. = Sulphide; Carb. = Carbide; Spheroid. = Spheroidized

TABLE 6—*Relative Rates of Wear of Nine Steel Compositions Containing Retained Austenite*
(168 Hr Wear Test in 6½ × 15-ft Mill at Phelps Dodge Corp., Ajo, Ariz.)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent								Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	S	P	
	(a) Forged Steel											
1	Oil Quenched from forge, T. 375°F	Martensite, bainite, austenite	627	1.01	0.44	1.06	0.21		0.34			90
2	Oil Quenched from forge, T. 375°F	Martensite, bainite, austenite	578	1.03	1.32	1.06	0.22		0.40			92
3	Forged, reheated, W.Q., T. 300°F	Martensite, austenite	652	0.80	0.60		0.29		0.26			100 Std.
	(b) Cast Steel											
4	Chill cast, air cooled	Austenite, bainite, trace pearlite	364	0.90	1.68	2.85	0.41		0.58	0.02*	0.04*	94
5	Chill cast, air cooled	Austenite, bainite, pearlite	452	0.96	1.68	3.43	0.32		0.65	0.03*	0.04*	94
6	Chill cast, air cooled	Bainite, austenite	512	0.88	0.97	1.56	0.33	0.59	0.92	0.03*	0.04*	96
7	Chill cast, W.Q. ½ min. air cooled	Bainite, austenite, globular sulph.	555	1.00	1.21		0.30*		0.35*	0.06*	0.17*	97
8	Chill cast, water quenched	Martensite, austenite, G.B. sulph.	627	0.95	0.90				0.35*	0.06*	0.17*	98
9	Chill cast, water quenched	Martensite, austenite, G.B. sulph.	682	0.90	0.85				0.35*	0.06*	0.17*	99

* Approximate analysis.

hardening of Hadfield manganese steel. This steel has shown relatively poor wear resistance in all our wear tests in which it has been included. This is observable from the abrasion factors for item 7 of Table 3, from item 42 of Table 4, and items 31 or 32 of Table 5. The influence of the carbon content on this type of austenitic steel has not been investigated by us.

One should not conclude from the results for Hadfield manganese steel that all types of austenite will have poor wear resistance when tested as grinding balls. Other types of austenite, which tend to transform quite readily to martensite when work hardened, exist at room temperature. Many of the groups of balls which we have tested contained austenite of this latter type. These groups have in all cases stood at the top of the list insofar as wear resistance is concerned, which leads us to believe that those types of austenite which will transform readily to martensite when cold worked are not harmful to wear resistance of grinding balls. This is demonstrated in Table 6 which lists the results obtained from nine steel compositions containing retained austenite.

The groups of balls listed in Table 6 were selected from Table 5. Tables 3 and 4 list a number of additional results on groups which contained retained austenite. It will be noted that these groups all show excellent wear resistance.

Some of the most wear resistant groups of balls in our tests had relatively low initial hardness because of their large amount of retained austenite. These balls have shown a substantial amount of work hardening on their surface as determined by Rockwell C impressions. For instance the balls in item 8 of Table 5 had a hardness of 40–41 Rc before testing. After a series of wear tests, which concluded with the test at Ajo, the balls in this group had surface hardnesses in the range of 50–56 Rc. Similarly, the surface hardness of the balls in item 10 of Table 5 increased from 53–55 Rc to 61–64 Rc. These surface hardness readings are possibly low since the Rockwell C impressions have probably penetrated into the softer metal below the surface. Balls which did not contain retained austenite showed no appreciable work hardening at the surface, as measured by the Rockwell C test.

To study more fully the influence of retained austenite in the matrix of grinding balls, tests were run on five steel compositions of varying austenite stability. The composition, heat treatment and hardness of these steels, together with the abrasion factors obtained from them on a wear test in the test mill at Golden, are given in Table 7. The groups are listed in order of decreasing austenite stability. Group 1-WQ represents austenitic manganese steel water quenched directly from the mold. It was completely austenitic except for a small amount of primary carbide around the dendritic grain boundaries. The relatively high rate of wear which we obtained from this type of austenite is similar to that obtained from items 31 or 32 of Table 5.

Microscopic observation and magnetic permeability tests indicated that groups 2-WQ and 2-AQ were similar and were completely austenitic except for some primary carbides around the dendritic grain boundaries. Magnetic permeability tests indicated that a slight amount of transformation to martensite occurred in group 2-WQR when it was refrigerated to −70°F (−57°C). Small specimens of steels 2-WQ and 2-AQ could be work hardened to a maximum of 44 Rc by hammering. This work hardening brought about some transformation to ferromagnetic products, indicating the formation of martensite.

Tests similar to those run on the three groups of composition 2 were also run on the three groups of composition 3. Groups 3-WQ and 3-AQ appeared to be completely austenitic except for the primary carbides around the grain boundaries. Group 3-WQR showed appreciable transformation

TABLE 7—*Relative Rates of Wear on Five Steel Compositions of Varying Austenite Stability*
(24-hour Wear Test in 3½ × 2 ft Mill at Golden Washed Pea Gravel Abrasive, 72.5 Pct Solids)

Group No.	Heat Treatment	Microstructure	Hardness* (Rc)	Analysis, Per Cent						Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	
1-WQ	Chill cast, water quenched	Austenite, grain boundary carbide	12	1.15	13.00				0.60	154
2-WQ	Chill cast, water quenched	Austenite, grain boundary carbide	20	1.04	1.10	10.76	1.11	3.94	1.10	120
2-WQR	Chill cast, water quenched, refrig. −70°F	Austenite, grain boundary carbide	23	1.04	1.10	10.76	1.11	3.94	1.10	120
2-AQ	Chill cast, air cooled	Austenite, grain boundary carbide	22	1.04	1.10	10.76	1.11	3.94	1.10	121
3-WQ	Chill cast, water quenched	Austenite, grain boundary carbide	23	0.96	1.35	9.48	1.08	1.53	0.90	105
3-WQR	Chill cast, water quenched, refrig. −70°F	Austenite, martensite, G.B. carbide	37	0.96	1.35	9.48	1.08	1.53	0.90	105
3-AQ	Chill cast, air cooled	Austenite, grain boundary carbide	23	0.96	1.35	9.48	1.08	1.53	0.90	104
4-AQ	Chill cast, air cooled	Martensite, bainite (?), austenite	51	0.72	0.70	2.60	0.36	0.32	0.74	96
5-WQ	Forged, reheated, water quenched, T. 300°F	Martensite, austenite	62	0.80	0.60		0.29		0.26	100 Std.

* This represents the hardness of the metal before it was cold worked by the wear test.

to martensite on cooling to −25°F (−32°C) and additional transformation when cooled to −70°F (−57°C). This is also indicated by the higher hardness of group 3-WQR. Groups 3-WQ and 3-AQ could be work hardened to 53 Rc by hammering, and also showed substantial transformation to ferro-magnetic products. It is clear from these tests that the austenite in the groups of composition 3 was less stable than that of composition 2. This was apparently caused by the higher nickel content of composition 2, since there was very little difference in the content of the other austenite stabilizing elements (carbon, manganese, and chromium) in the two compositions.

Group 4-AQ contained fairly substantial amounts of austenite of relatively low alloy content. It is reasonable to expect that this austenite would be rather unstable and, therefore, easily subject to transformation to martensite when work hardened.

Group 5-WQ was our standard martensitic forged steel with which all test groups are compared. It represents mainly martensite in a mildly tempered condition. This mild temper consisted of a brief reheat at approximately 300°F (150°C) which each ball received as a result of its removal from the water quench before its center was completely cooled.

The wearing characteristics of the groups listed in Table 7 improve with decreasing stability of the retained austenite and reach an optimum in group 4-AQ which represents a relatively low alloy steel containing appreciable amounts of retained austenite. The type of martensite found in group 5-WQ causes a slight falling off in wear resistance.

Refrigeration had no effect on the wear resistance of group 3-WQR even though it raised the initial hardness from 23 Rc to 37 Rc. However this steel was subjected to cold work by the forces of impact involved in the wear test which may have raised its hardness at the wearing surface to a value above 50 Rc. A substantial amount of work

hardening occurred on the surface of all the austenitic balls though to such a shallow depth that we were unable to measure the surface hardness with any reasonable degree of accuracy.

It has been brought out that retained austenite at the wearing surface of low alloy, high carbon steel grinding balls will transform to martensite by the cold working effect which normally exists in a ball mill grinding operation. This retained austenite can also be transformed to martensite by refrigeration though the one result of such treatment, obtained from group 3-WQR in Table 7, does not indicate that transformation in this manner will appreciably improve the wear resistance of grinding balls.

Another method used for transforming retained austenite was to temper it for a short time at 600°F (315°C). The influence of tempering treatments up to 600°F (315°C) on the wear rates and hardnesses of three martensitic or bainitic steel compositions containing retained austenite is shown in Table 8. Tempering these compositions at 375°F (190°C) brought about a slight increase in hardness but very little, if any, change in wear resistance. By tempering the compositions at 600°F (315°C), however, the austenite in the steel was transformed to tempered martensite or bainite. Little overall change in hardness occurred as a result of this treatment. A marked drop in wear resistance did occur, however, with the average rate of wear for the three compositions almost doubling as a result of the 600°F (315°C) temper.

It should be noted that the wear tests listed in Table 8 were batch runs in a crushed feldspar abrasive. This abrasive was selected because abrasion tests run in feldspar tend to show a wide spread between balls of different wearing quality. This allows the detection of relatively minor differences in the wearing quality of balls. In this series of 6-hr tests the amount worn off the balls was quite small so that the limit of experimental error was about ±5 pct. For this reason we have listed wear rates in Table 8 instead of abrasion factors which require a higher degree of accuracy.

The abrasives and operating conditions in many commercial ball mills are such that the loss in wear resistance caused by the tempering of hardened balls at 600°F (315°C) will be much less than that shown for Table 8. For instance in Table 4, items 25, 26, 30, and 31 represent groups of balls which contained martensite or bainite plus retained austenite before they were tempered. Item 25 in Table 4 is also represented as item 19 in Table 5. These groups do not have as good wear resistance as we would expect from them if they had not been tempered. However, their loss in wear resistance was obviously not very great since they still show relatively good abrasion factors.

Further tests, of a more comprehensive nature, on the influence of tempering hardened steel balls should have practical value. Antia, Fletcher and Cohen[9] have demonstrated that three separate tempering reactions occur between 180°F (80°C) and 675°F (355°C). A study of the wear resistance of the hardened steel before and after each of the tempering reactions should be of value.

The influence of carbon content on steels and irons having a matrix of martensite, bainite or austenite is of interest. This variable has not been fully investigated over the entire range of compositions by our tests. Quite a few martensitic steels within the range of 0.70 to 0.90 pct carbon have, however, been tested and found to be remarkably similar in wearing characteristics. It was for this reason that we chose a martensitic steel within this range of carbon content as our test standard.

When the carbon content of a martensitic steel was dropped to 0.60 pct or lower a definite falling off in wear resistance was noted. Martensitic 0.50 to 0.60 pct carbon low alloy steels when tested by grinding

TABLE 8—*Influence of Tempering on the Wear Rates of 4 Groups of Hardened Steel Balls*
(Averages from Two 6-hr Wear Tests in 3 × 2-ft Mill at Golden. Feldspar Abrasive. 70 pct Solids)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent					Wear Rate Grams per 100 Sq Cm per Test
				C	Mn	Cr	Mo	Ni	Si	
1-a	O.Q. from forge	Martensite, bainite (?), austenite	606	1.01	0.44	1.06	0.21		0.34	0.7
1-b	O.Q. from forge temper 375°F. 1 hr	Martensite, bainite (?), austenite	627	1.01	0.44	1.06	0.21		0.34	0.7
1-c	O.Q. from forge temper 600°F. 1 hr	Bainite (?), Tempered martensite	600	1.01	0.44	1.06	0.21		0.34	1.5
2-a	O.Q. from forge	Martensite, bainite (?), austenite	482	1.03	1.32	1.06	0.22		0.40	0.8
2-b	O.Q. from forge temper 375°F. 1 hr	Martensite, bainite (?), austenite	578	1.03	1.32	1.06	0.22		0.40	0.8
2-c	O.Q. from forge temper 600°F. 1 hr	Bainite (?), Tempered martensite	578	1.03	1.32	1.06	0.22		0.40	1.2
3-a	Chill cast, air cooled	Bainite, austenite	642	0.73	0.95	1.84	0.42	0.99	0.47	0.7
3-b	Chill cast, air cooled, tempered 375°F	Bainite, austenite		0.73	0.95	1.84	0.42	0.99	0.47	0.7
3-c	Chill cast, air cooled, tempered 600°F. 1 hr	Bainite, tempered martensite	555	0.73	0.95	1.84	0.42	0.99	0.47	1.3
4-a	Forged, re-heated, water quenched, T. 300°F	Martensite, austenite	652	0.88	0.50		0.20			0.8 Std.

river sand in the test mill at Golden or by grinding molybdenum ore at Climax have been found to wear from 5 to 15 pct faster than our standard 0.80 pct carbon, low alloy martensitic steel.

When the carbon content of a martensitic steel was raised to about 1.0 pct the wear resistance of the steel was somewhat better than that of our standard. Such steels generally have a very substantial amount of retained austenite in their structure.

High carbon steels containing over 0.90 pct carbon suffer from the disadvantage of brittleness and susceptibility to quench cracking. Recent tests have indicated that reduced cracking of the high carbon steel would be obtained by quenching the balls from a temperature just above the Ac1 to produce a structure of spheroidized carbides in martensite. A limited amount of data which we have on this structure indicates that it has somewhat better wear resistance than martensitic steels of eutectoid composition. This is in line with experience in the ball bearing field and with experience on the wearing properties of rock drill bits for percussion drilling.

It has been found that relatively high alloy contents are necessary for the production of a matrix of martensite, bainite, or austenite in high carbon irons. Chromium and molybdenum, at least up to a certain amount, are contained principally within the massive primary carbides, having little effect on the matrix structure. Nickel is effective on the matrix structure and is, therefore, used to produce "Ni-Hard" white irons with a matrix of martensite plus austenite. Chromium is used in these Ni-Hard irons to suppress the formation of graphite in the structure. Two typical Ni-Hard irons are listed as items 1 and 4 in Table 3 and items 48 and 43, respectively, in Table 4.

2. *Balls with a Pearlitic Matrix*

Generally speaking, balls with a pearlitic matrix will be inferior in wear resistance to

those with a matrix of martensite or bainite, plus retained austenite. A very large proportion of the grinding balls used commercially is, however, still of the pearlitic type so the characteristics of such balls have been rather fully investigated. The inferior wearing characteristics of the pearlitic steels and irons are quite evident from a study of the data in Tables 3, 4, and 5. It is also evident, however, that there is a rather wide range in wearing characteristics of various pearlitic steels and irons. Some of the harder, high carbon pearlitic steels are capable of giving a fairly good account of themselves in the harder types of ore. In grinding the softer types of abrasives, such as feldspar or calcite, none of the pearlitic steels or irons showed up well in comparison with the standard martensitic steel balls.

Pearlitic steels of eutectoid carbon content tend to wear better with increasing fineness of the lamellar structure which is paralleled by an increase in the hardness of the steel. This is indicated by a comparison of items 6 and 8 in Table 3.

The influence of carbon content on the wear resistance of six pearlitic forged steels of similar hardness is demonstrated by Table 9. The trend towards improved wear resistance as the carbon content is raised from 0.52 to 1.03 pct is very consistent. Further data on the influence of carbon content on the wear resistance of a series of alloyed pearlitic steels of relatively high hardness are given in Table 10. Again the trend towards improved wear resistance as the carbon content increases, in this case up to 1.19 pct, is observable.

The results in Table 11 are shown to illustrate the influence of carbon content up to the cast iron range on balls having a pearlitic matrix. Further data on the performance of pearlitic white iron balls are also given in Tables 3, 4, and 5. It will be noted from these data that the introduction of sufficient carbon into a composition to cause the formation of primary massive carbides in its structure generally causes a definite loss in wear resistance.

Data on the influence of carbon content on the wear resistance of pearlitic balls are presented by Prentice.[5] While Prentice does not report the microstructure of the balls he tested, there are certain groups in his list which, because of their analysis, heat treatment and hardness obviously have a pearlitic matrix. Six of these groups are re-listed in Table 12. The superiority of the steel of eutectoid or slightly hypereutectoid carbon content is evident.

The most wear resistant balls of the pearlitic type are made of steel compositions of high hardness and hyper-eutectoid carbon content. A maximum hardness of about 477 Bhn was obtained in a purely pearlitic steel when its carbon content was in a range of 1.0 to 1.40 pct. All of our pearlitic steels within this carbon range contained an envelope or partial envelope of pro-eutectoid carbides around the grain boundaries. Such carbides are very effective in causing rapid nucleation of the austenite, so in this respect they promote the development of a pearlitic matrix. If large amounts of the pro-eutectoid carbides precipitate at the grain boundaries they will lower the wear resistance of the steel. It is apparently desirable to retain most of this pro-eutectoid carbon within the pearlitic matrix. The judicious use of alloying elements coupled with rapid cooling through the critical range has been found quite effective in accomplishing this.

The data in Table 10 indicate that a high carbon, low alloy pearlitic steel is capable of showing fairly good wear resistance when tested in Climax ore. This is confirmed by the result for item 32 in Table 4 as well as by numerous unlisted results. It should be mentioned, however, that when the softer types of ore are ground (such as some of the porphyry copper ores) none of the pearlitic steels will compare very favorably with the

TABLE 9—*Influence of Carbon Content on the Wear Rates of Six Pearlitic Forged Steel Compositions*
(145-hr Wear Test in a 6 × 6-ft Mill at Climax, May 1941)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent						Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	
1	Air cooled from forge	Fine pearlite, grain boundary ferrite	340	0.52	1.45	0.85			0.19	126
2	Oil quenched from forge	Fine pearlite, a little ferrite	375	0.70	0.66				0.15	116
3	Oil quenched from forge	Fine pearlite	375	0.71	0.63				0.22	115
4	Air cooled from forge	Fine pearlite	387	0.75	0.45	0.42	0.26		0.65	114
5	Air cooled from forge	Fine pearlite, G.B. carbide	364	1.01	0.44	1.06	0.21		0.34	110
6	Air cooled from forge	Fine pearlite, G.B. carbide	387	1.03	1.32	1.06	0.22		0.40	109

TABLE 10—*Influence of Carbon Content on the Wear Rates of Five Pearlitic Cast Steel Compositions (Low Metalloid)*
(150-hr Wear Test in a 9 × 8-ft Marcy Low Discharge Mill at Climax, August 1945)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent						Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	
1	Chill cast, air cooled	Fine pearlite	430	0.74	0.57	1.24	0.20		0.67	117
2	Chill cast, air cooled	Fine pearlite	418	0.91	0.61	1.37	0.21		0.47	111
3	Chill cast, air cooled	Fine pearlite, G.B. carbide	422	1.02	0.76	1.37	0.20		1.46	111
4	Chill cast, air cooled	Fine pearlite, G.B. carbide	426	1.07	0.62	1.20	0.21			111
5	Chill cast, air cooled	Fine pearlite, G.B. carbide	424	1.19	0.71	1.32	0.22		0.96	106

TABLE 11—*Influence of Carbon Content on the Wear Rates of Seven High Metalloid Cast Steels and Irons*
(145-hr Wear Test on a 6 × 6-ft Mill at Climax, May 1941)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent								Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	S	P	
1	Sand cast, cooled in sand	Pearlite, Grain boundary sulphide	364	0.99	0.55	2.69	0.35		0.50	0.19	0.33	119
2	Sand cast, cooled in sand	Pearlite, G.B. sulphide and carbide	387	1.24	1.03	2.63	0.28		0.36	0.12	0.31	122
3	Sand cast, cooled in sand	Pearlite, mass. carbide, globular sulphide	401	1.53	1.68	2.56	0.54		0.47	0.16	0.32	127
4	Sand cast, cooled in sand	Pearlite, mass. carbide, globular sulphide	415	1.53	1.66	2.6	0.26		0.49	0.17	0.33	130
5	Sand cast, cooled in sand	Pearlite, G.B. sulphide and carbide	460	1.54	2.92	1.10			0.51	0.15	0.26	141
6	Sand cast, cooled in sand	Fine pearlite, massive carbide	532	3.00	1.51	1.94		2.75	0.64	0.13	0.29	151
7	Sand cast, cooled in sand	Pearlite, steadite, massive carbide	477	3.00	0.65	0.80	0.25		0.90	0.17	0.40	176

TABLE 12—*Influence of Carbon Content on the Wear Rates of Six Pearlitic Steels and Irons, from Prentice*[5]
(Wear Test in a 32 × 17-in. Mill at City Deep Ltd., Johannesburg)

Test No.	Heat Treatment	Probable Microstructure	Hardness (Rc)	Analysis, Per Cent						Life (Days)
				C	Mn	Cr	Si	S	P	
28	Forged, air cooled (?)	Fine pearlite	40	0.90	0.89	0.85	0.20	0.03	0.04	147
35	Rolled, air cooled	Fine pearlite	35	0.78	0.87	1.10		0.05	0.07	120
20	Rolled, air cooled	Fine pearlite	34	0.65	0.59	2.10	0.90	0.03	0.04	119
22	Rolled, air cooled	Pearlite	27	0.53	1.53	0.28	0.11	0.03	0.05	113
7	Rolled, water quenched	Pearlite, grain boundary ferrite	33*	0.53	0.30		0.24	0.05	0.05	87
29	Cast, Sand cooled (?)	Pearlite, Massive carbide	44	3.14	0.50	Tr	0.30	0.16	0.13	83

* This was the hardness near the center of these halls. They were probably harder near their surface.

compositions containing a matrix of martensite or bainite, plus retained austenite.

3. *Balls Containing Spheroidal Carbides*

Spheroidal carbides may be developed in steel compositions by tempering martensite or bainite or, under certain circumstances, by direct transformation from austenite as described by Payson, Hodapp and Leeder.[7] Indications from our tests are that these spheroidal structures are not as wear resistant as lamellar (pearlitic) structures of the same hardness. A comparison of the wear resistance of three compositions which were heat treated to develop lamellar (pearlitic) and spheroidal structures of approximately equal hardness is given in Table 13. The poorer wear resistance of the spheroidal (tempered martensite) structures is evident.

TABLE 13—*Relative Wear Rates of Lamellar and Spheroidal Structures of Approximately Equal Hardness*

(145-hr Wear Test in a 6 × 6-ft Mill at Climax, May 1941)

Analysis, Per Cent					Lamellar Structure (Air Cooled from Forge, Pearlitic)		Spheroidal Structure (Oil Quenched, Tempered 1050°F. Tempered Martensite	
C	Mn	Cr	Mo	Si	Hardness (Bhn)	Abrasion Factor	Hardness (Bhn)	Abrasion Factor
0.75	0.45	0.42	0.26	0.65	387	114	387	124
1.01	0.44	1.06	0.21	0.34	364	110	387	113
1.03	1.32	1.06	0.22	0.40	387	109	402	113

An exception to the theory that spheroidal structures tend to have inferior wear resistance may be found in the case of structures in which the spheroidal carbides exist in a matrix of martensite. (*See* (1) *above.*)

The Influence of Grain Size

In steel compositions the prior austenitic grain size of the structure seems to have no influence on the wear resistance of grinding balls provided the microstructure within the grains is the same. This has been demonstrated on both cast and forged balls of various types. A rough classification of the steel balls we have studied in order of decreasing grain size follows: 1. Sand cast steel, as cast. 2. Chill cast steel, as cast. 3. Forged steel, as forged. 4. Forged or cast steel, reheated between 1400 and 1600°F (760–870°C) and quenched in air, oil or water.

Numerous tests have been run in which all four types of steel, similar in composition and microstructure, were included. No appreciable difference in the wear resistance of the four types has been found. Under severe conditions of impact, however, the martensitic or bainitic coarse-grained types often failed by spalling or breakage. Pearlitic steels, irrespective of their grain size, have not spalled or broken on any of our tests. For the martensitic steels, however, indications are that a grain refining heat treatment is desirable on balls which must withstand severe conditions of impact or combinations of impact plus low rates of wear such as are encountered in the grinding of limestone or other very soft abrasives.

Grain size is an important factor governing the wear resistance of cast white iron balls. This is particularly true for cast white iron with a pearlitic matrix. Sand cast pearlitic white iron balls have always had poorer wear resistance than chill cast pearlitic iron in our tests. It is believed that the very coarse primary carbides which exist in sand cast white iron are responsible for this more rapid rate of wear. These

carbides may be more subject to spalling on a microscopic scale.

The wear of white iron with a matrix of martensite plus retained austenite does not appear to be so greatly influenced by grain size. It will be noted in a comparison of items 1 and 4 of Table 3 that this particular sand cast Ni-Hard white iron actually wore less than the chill cast Ni-Hard white iron.

Where severe impact occurs in a ball mill or where very large balls are used to accomplish crushing as well as grinding, breakage or spalling of all types of white iron may be expected. White iron of the Ni-Hard type seems to be somewhat more resistant to this spalling and breakage than the pearlitic types of white iron.

The Influence of Alloying Elements

Since microstructure is the dominating factor determining the wear resistance of grinding balls, we believe the primary function of alloying elements is to assist in obtaining the type of microstructure desired. A secondary function of alloying elements may be to provide corrosion resistance or to facilitate the development of an abrasion resistant oxide film on the balls.

The influence and usefulness of alloying elements will be considered for the two microstructural types of grinding balls which have, in our estimation, shown the best economic possibilities. These are: 1. Balls with a matrix of martensite plus retained austenite or bainite plus retained austenite. 2. Balls with a pearlitic matrix.

Balls of type 1 are generally superior to even the best of those of type 2 insofar as wear resistance is concerned. Impact conditions in certain ball mills may, however, be too severe for balls of type 1 particularly if they are coarse grained.

To produce the type 1 microstructures in grinding balls, they must be of a composition which possesses sufficient hardenability to halt transformation to pearlite during their final air or liquid quench from the austenitic state. To accomplish this without resorting to too drastic a quench it is necessary to have alloying elements present in practically all the sizes of grinding balls down to about 1 in. diam. Many combinations of alloying elements can be used. However, the selection of an alloy or alloy combination together with the type of quench should be such that it introduces a minimum of harmful effects into the balls. The development of high residual stresses or quench cracks and the presence of embrittling elements such as phosphorus, sulphur or excessively high manganese and silicon should be avoided. Overstabilization of the retained austenite in the structures should also be avoided.

Numerous compositions and methods of heat treatment used to produce the type 1 microstructures in steel or iron balls 3 in. in diam are to be found in Tables 4 to 8 inclusive. It should be noted, however, that the groups listed in these tables were tested because they contributed to the study of certain variables. In most cases these groups do not represent the best composition or heat treatment for commercial production. The commercial manufacture of some of these groups would involve an unnecessarily high alloy cost, while others, because of their composition, grain size or heat treatment, would produce balls subject to quench cracking or other forms of brittleness.

The most economical alloying element per unit of hardenability effect is manganese. We have found that this element can be used to advantage in amounts up to about 0.80 pct in grinding balls with the type 1 microstructures. Larger amounts of manganese than this are generally undesirable since they tend to cause quench cracking or spalling and breakage of the balls in service. In cast steel balls, silicon contents in excess of 0.70 pct have been found undesirable for the same reasons. The cause

of this may be that such high silicon contents were generally associated with an over-reduced condition during the finishing period in the melting furnace. For hardenabilities greater than that obtainable from 0.80 pct manganese plus 0.70 pct silicon we believe the combined use of chromium, molybdenum and nickel will give the best results. Copper, in amounts up to 0.50 pct, has also been used to advantage in cast steel balls.

To determine the most efficient chromium, molybdenum and nickel combinations for commercial production of cast or forged steel balls with the type 1 microstructures, we have found that Hostetter's method[10] can be applied to good advantage. While Hostetter's method of calculation was developed to determine the most economical combinations, we have found that such combinations have also worked well from a performance standpoint insofar as wear resistance and freedom from quench cracking or breakage in service are concerned. In the interest of obtaining greater toughness in the hardened balls, certain steel ball producers prefer, however, to deviate from Hostetter's formula by replacing a part of the chromium with a further addition of molybdenum. It is thought that since molybdenum has very little effect in lowering the temperature range in which austenite begins to transform to martensite, it should be less likely to induce quench cracking or high residual stresses in balls which are quenched to below their Ar'' temperature.

Interrupted quenching techniques, which tend to avoid the development of quench cracks or high residual stresses, can be used to advantage in the production of alloyed balls with the type 1 microstructure. They are particularly useful on coarse grained steels such as those in the as-cast or as-forged condition. A technique which we have used with good success on eutectoid carbon, low alloy, chromium molybdenum steel balls has involved a quench in oil, water sprays, or moving air until the surface of each ball was down to between 600 and 700°F (305–370°C). The balls contained sufficient alloy content to suppress any transformation to pearlite so that they were still completely austenitic at these temperatures. The balls were then removed from the quench and allowed to cool slowly to room temperature. The transformation from austenite to bainite or martensite occurred during the slow cooling period. Usually, the balls became quite strongly ferro-magnetic while they were still at temperatures between 700 and 500°F (370–260°C), indicating that the transformation product was mostly bainite.

For steel compositions, it has been pointed out that martensite (or bainite) plus an unstable austenite is easily obtained by the addition of relatively small amounts of alloying elements. Whether the further addition of alloying elements is beneficial or not is of interest. Our tests show little improvement for any large addition of an alloying element, particularly when economic factors are considered. Chromium additions beyond that necessary for full hardening are probably beneficial when conditions are such that the removal of oxide films on the balls represents a substantial proportion of the wear. In most of our tests, however, the effect of chromium in amounts greater than that necessary for full hardening has been small.

The addition of large amounts of manganese or nickel to a full hardening steel analysis appears to be undesirable because of stabilization of the retained austenite. Molybdenum additions beyond that necessary for full hardening have shown no appreciable effect on wear resistance.

The full possibilities for the carbide-forming elements when applied in a structure of martensite plus spheroidized carbides have not been explored. Fairly highly alloyed compositions, such as those used in high-speed steel cutting tools, may

show superior wear resistance though the field of application for such costly compositions in grinding balls seems to be decidedly limited.

Alloying elements in the 1.0 to 1.4 pct carbon pearlitic balls serve to increase the fineness of the pearlitic structure and also to increase its carbon content by partially suppressing the rejection of pro-eutectoid carbides around the original austenite grain boundaries. Alloying elements such as chromium and molybdenum may have a secondary beneficial effect on pearlitic structures by the introduction of alloy carbides. Since much work remains to be done, about all that can now be said is that combinations of chromium in a range of 1.0 to 3.0 pct plus molybdenum in a range of 0.20 to 0.50 pct have given good results. Manganese has also been used in amounts up to 2.0 pct though our tests have indicated that its use above 1.0 pct has contributed little to the wear resistance of these hard pearlitic steels. The nickel which was present in many of our pearlitic compositions in amounts up to 1.0 pct apparently had little influence on wear rates.

Balls made from 1.0 to 1.4 pct carbon low alloy steels may be subjected to a fairly wide range of cooling rates from their austenitic state, while still developing a hard pearlitic structure. A fairly wide range in total alloy content is also permissible. Such balls will, therefore, lend themselves well to production under conditions where a simple fool-proof heat treatment, such as an air quench, is required.

Because of the presence in white iron of massive primary carbides which tend to rob the matrix of its carbide forming alloying elements, Hostetter's formulas do not apply. A combination of nickel in a range of 3.0 to 4.5 pct plus chromium in a range of 1.5 to 2.5 pct (the Ni-Hard irons) has been used quite successfully to produce white iron with a matrix of martensite plus retained austenite.

The Influence of the Metalloids

As might be expected, the presence of phosphorus and sulphur above the usual limits is undesirable in steel balls. Both elements cause brittleness in steel and also injure the hot working properties of wrought steels. Table 14 gives a comparison between a number of low metalloid, and similar high metalloid, pearlitic alloy steels. The high metalloid compositions are definitely inferior in wear resistance, even though their structure, hardness, and carbon content are similar. In Table 5, a high metalloid pearlitic steel represented by item 30 compared unfavorably with items 4, 5, 25, and 26, which represent low metalloid pearlites of approximately the same hardness.

The martensitic steels appear to be less affected by metalloids than the pearlitic steels insofar as wear resistance is concerned. In Table 5, the martensitic steels of high metalloid content are represented by items 11 to 17. These groups had good wear resistance, but the balls in these high metalloid groups were very subject to quench cracking and also to breakage in our wear tests.

White iron balls generally have a relatively high sulphur and phosphorus content. Whether any improvement in their wear resistance could be obtained by lowering their metalloid content is not known.

The Influence of Abrasives on Wear Resistance

By changing from one type of abrasive to another, very marked differences in the relative wear resistance of the various types of balls have been observed. While the order of merit of a series will generally remain the same, the spread between the performance of a good and poor type will generally be much greater when grinding soft than when grinding hard abrasives. This is readily observable from the data in Table 3. Other tests which have been run

TABLE 14—*Relative Wear Rates of Pearlitic Steels of High and Low Metalloid Content*

(145-hr Wear Test in a 6 × 6-ft Mill at Climax, May 1941)

Group No.	Heat Treatment	Microstructure	Hardness (Bhn)	Analysis, Per Cent							Abrasion Factor
				C	Mn	Cr	Mo	Ni	Si	S	P	
	(a) Low Metalloid Steels											
1	Sand cast, cooled in sand	Fine pearlite	352	1.06	1.51	2.63	0.53		0.44	0.02	0.04	106
2	Sand cast, cooled in sand	Fine pearlite	341	1.06	2.02	3.05	0.26		0.42	0.05	0.01	107
3	Sand cast, cooled in sand	Fine pearlite, G.B. Carbide	388	1.29	1.03	1.60	0.42	0.99	0.41	0.03	0.06	109
4	Sand cast, cooled in sand	Fine pearlite	375	0.91	1.04	1.66	0.43	0.78	0.61	0.02	0.04	110
5	Sand cast, cooled in sand	Fine pearlite	369	0.78	0.93	1.63	0.48	0.87	0.44	0.02	0.04	111
	(b) High Metalloid Steels											
6	Sand cast, cooled in sand	Pearlite, G.B. Sulphide	364	0.99	0.55	2.69	0.35		0.50	0.19	0.33	119
7	Sand cast, cooled in sand	Pearlite, G.B. Sulphide and Carbide	387	1.24	1.03	2.63	0.28		0.36	0.12	0.31	122
8	Sand cast, cooled in sand	Pearlite, G.B. Sulphide	331	1.02	0.50	0.19	0.57	1.04	0.42	0.17	0.30	130

in calcite, cement rock, and in commercial ores high in feldspar or talc, tend to confirm this. Ellis' data[1] confirm this observation.

A reversal in order of merit may occur among the pearlitic steels and pearlitic white irons when we change from grinding a hard abrasive to the softer abrasives. For instance, in the grinding of quartz or ores high in quartz content, the pearlitic steels are generally superior to pearlitic white iron. When grinding pure feldspar, however, this condition may be reversed. This is observable from a comparison of items 6 and 10 in Table 3.

Possibly an explanation for the way that the various abrasives influence the wear resistance of grinding balls may be obtained by a consideration of the relative indentation hardness of minerals and steel at various hardness levels. Peters and Knoop[11] list the following indentation hardnesses as obtained by microhardness tests with a diamond pyramid:

Calcite	135
Steel, Rc 25	276
Albite Feldspar	490
Steel, Rc 47	496
Orthoclase feldspar	560
Quartz	710–790
Steel, Rc 65–67	791

The foregoing table indicates that quartz has about the same hardness as the hardest steel, so it should be capable of scratching all types of steel. Feldspar minerals, which have a lower hardness than quartz, will not, according to mineralogical theory, scratch the hard martensitic steels but should scratch steels softer than about 50 Rc. This probably accounts for the fact that, in a feldspar abrasive, the martensitic steels show outstanding superiority, whereas, in grinding quartz, which is capable of scratching all steels, the superiority of the martensitic steels is not so great.

A further confirmation of this scratch theory of wear is provided by the wear rates on balls grinding calcite, which is softer than all the steel balls we have studied. Theoretically, no wear should

occur on the balls when grinding calcite. Actually some wear did occur in our tests but the wear rate was only about one tenth of that in feldspar and only about one half that of the balls when they were run in water without any abrasive. The calcite, therefore, acted more as a lubricant than as an abrasive.

Other factors which we have found to affect the spread in wear resistance obtained between a good and a poor type of ball are the coarseness of the abrasive and the pulp density in wet grinding operations. An increase in the coarseness of the abrasive has been found to increase this spread. A decrease in pulp density (more dilution by water) was found to increase this spread on a series of tests in the 3-ft diam. mill at Golden using Climax ore or washed river sand as abrasive. Whether this can be taken as a general rule for all mills or abrasives is not known. When the balls were tested in clear water the rate of wear on all balls dropped to about 10 pct of the rate of wear obtained when Climax ore was used as the abrasive.

Practical Adaptability of the Short Time Wear Test

Our use of the short time wear test described in this paper has been both for the study of fundamental factors influencing the wear of balls, and for an evaluation of the merits of the types of balls which are available in commercial quantities. Resistance to wear, spalling and breakage may be studied by this test. Where possible, it is preferable to run these short time tests under normal service conditions in commercial ball mills. The test has been found very useful as a means for the selection and routine inspection of grinding balls. The method could also be applied with minor modifications to the selection and inspection of grinding rods for rod mills.

In the development of alloys for use in parts other than grinding balls which are subject to abrasive wear, this short time wear test may have possibilities provided the wearing forces on the part in question are similar to those on a grinding ball. In this connection we have studied alloy steels for ball mill liners by testing the desired composition and structure in the form of balls 5 in. in diam. Where comparisons are available the relative wear resistance of a given composition and structure as established by this short time test on large balls has shown good agreement with actual service for the same composition and structure when tested as a liner in the same mill.

A number of correlations between the results of our small scale tests on balls and large scale tests in commercial mills are already available. The results from two commercial mills are given in Table 15.

TABLE 15—*Correlation between Relative Rates of Wear, Determined by Large and Small Scale Wear Tests in Two Commercia Mills*

Type of Ball	Relative Rates of Wear*	
	Large Scale Test	Small Scale Test
(a) Primary Grinding of Crushed Molybdenum Ore at Climax, Colorado		
Martensitic Forged Steel (Standard)	100	100
Fine Pearlitic Forged Steel	107–124	108–120
Sand Cast Cr-Mo White Iron	170–180	176
(b) Primary Grinding of Porphyry Copper Ore at Phelps Dodge Corporation, Ajo, Arizona		
Martensitic Forged Steel	100	100
Chill Cast White Iron	180–200	168–185

* Relative rates of wear on the large scale tests were calculated on the basis of the consumption of balls per ton of ore ground to a given fineness. For the small scale tests the relative rates of wear are calculated on the basis of weight lost per unit of surface area of the individual test balls in the same mill.

The agreement between the two types of testing is quite good. In the case of the test at Ajo, the correlation is better when we make allowances for the fact that the metal worn off each white iron ball during

the test was somewhat more wear resistant (because of the finer grain size near the chilled surface) than the remainder of the metal in the ball.

Summary

1. By running marked balls in a ball mill along with a group of standard balls of known quality, it is possible to determine the relative merits of any type of grinding ball within a short time.

2. Barring segregation, grinding balls wear in direct proportion to their surface area and therefore decrease in diameter at a constant rate.

3. A matrix of martensite or low temperature bainite, plus retained austenite, has shown the best wear resistance of all the types studied.

4. Spheroidized carbides enhance the wear resistance of a martensitic matrix.

5. The test results indicate that retained austenite is not an undesirable component of the matrix structure providing it is unstable enough to transform to martensite when cold worked.

6. The wear resistance of steel balls improves with increasing carbon content provided it is not rejected as a grain boundary carbide.

7. The prior austenitic grain size of steel balls does not appear to influence wear resistance. Since balls which have a fine austenitic grain size are less prone to fracture or spall from impact, such grain size is advocated for steel grinding balls.

8. Alloying elements affect the wear resistance of steel grinding balls indirectly through their ability to retard the rates of austenite decomposition at subcritical temperatures. The selection of alloying elements should depend upon their ability to develop the desired matrix structure under the conditions of heat treatment selected by the manufacturer.

9. The metalloids sulphur and phosphorus are undesirable constituents in all types of steel balls because they increase brittleness, impair the hot working properties of the steels, increase the tendency of a steel to quench crack, and decrease wear resistance.

10. The primary massive carbides which are formed during the solidification of pearlitic white cast iron are, in general, detrimental to wear resistance. They are more harmful in sand cast than in chill cast balls.

11. The spread between the performance of a structure of good wear resistance and one of poor wear resistance will vary greatly depending on the mineralogical characteristics of the ore or abrasive in the ball mill and also to some extent on such factors as abrasive size, pulp density and degree of impact. It is therefore desirable to run short time ball tests in the same mills where their use on a large scale is being contemplated.

12. Good correlation is obtained between results of short time tests and the results of large scale tests run over long periods of time.

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Kennecott Copper Corp.	McGill, Nev.
Miami Copper Co.	Miami, Ariz.
Phelps Dodge Corp.	Ajo, Ariz.

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