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Experiments in Hot-Rolling and Forging of Ductile Cast Iron

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and R. L. Crosby



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EXPERIMENTS IN HOT-ROLLING AND FORGING OF DUCTILE CAST IRON

by

L. A. Neumeier,¹ B. A. Betts,² and R. L. Crosby²

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ABSTRACT

The Bureau of Mines investigated hot-rolling and forging characteristics of experimental ductile iron castings, both sand and permanent-mold, made with charges containing up to 70 pct foundry pig iron and 95 pct steelmaking pig iron. Between 1,550° and 1,950° F, most castings could be rolled to 90-pct reduction or forged to 70-pct reduction without serious cracking. Charge and composition have less bearing on workability than on subsequent properties. Permanent mold castings could be worked as readily as sand castings at 1,750° and 1,950° F. Plasticity improved with temperature. Small billets were also forged cold to 50-pct reduction without cracking.

↑

With equivalent nodularity, composition affects properties of wrought materials by altering matrix structure and strength. Properties vary with reduction and improve with increasing working temperature. Rolled material has high strength and anisotropy, and low ductility, particularly in the transverse direction.

Annealing reduces strength and improves ductility, but anisotropy persists. At 70-pct reduction, impact resistance in the longitudinal direction is about twice that in the transverse. Annealing roughly doubles impact resistance. Deformation enhances damping capacity.

The feasibility of die-forging and bar-rolling of ductile iron was evaluated in trial tests conducted under a Bureau contract.

Although workability and ductility of ductile iron are inferior to those of steel, more advantage could be taken of ductile iron's plasticity to work rough shapes to final dimensions.

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INTRODUCTION

The present research was undertaken as part of the U.S. Department of the Interior, Bureau of Mines goals to minimize the requirements for mineral commodities through conservation and substitution, and to maximize productivity and reduce energy requirements of mineral processing.

Ductile iron, often called nodular cast iron, was discovered over 25 years ago. An historical review has been given relatively recently (11).³ Discovery of nodular cast iron made it possible for the first time to form graphite nodules directly during solidification. Mechanisms remain controversial, but processes are well established. Basically, low-sulfur melts with appropriate carbon, silicon, and manganese are nodulized shortly before casting by treating them with magnesium, usually in conjunction with some rare earth metals, and are graphitized with agents such as ferrosilicon. Production with a variety of techniques (17) has grown rapidly, to about 2-1/2 million tons annually in this country alone.

Unlike gray cast iron, which contains embrittling graphite flakes, the graphite nodules in ductile iron are dispersed in a continuous matrix (normally ferritic-pearlitic) similar to that of steel. This structure imparts toughness and ductility and permits plastic deformation.

Ductile iron is actually a family of materials, depending on composition, heat treatment, and other factors. It probably can be processed to the widest range of properties of any material (8). Compared with steel, it has generally inferior ductility, weldability, and impact and fatigue resistance, but superior castability (high carbon and silicon), machinability, wear and corrosion resistance, and damping capacity.

Since its inception, there has been scattered interest in assessing the workability of ductile iron; much of the interest has been abroad. In 1951, Perry (22) of Canada reported that ductile iron could be hot rolled and forged at 1,550° to 1,950° F (843° to 1,066° C), but that edge cracking limited yield. In the same period, Wakamoto (31) of Japan reported that ductile iron could be hot worked to 50-pct reduction, and Unksow (30) of the U.S.S.R. that rolling could be carried to 50-pct reduction and forging to 60-pct reduction. Chang Tso-mei (7) of China concluded that maximum deformation was related to reduction rate. In 1968, Sheffler (25) related property anisotropy to the extent of nodule deformation. Okabayshi (20) of Japan reported that a high-silicon ductile iron could be worked at 1,000° C (1,832° F). More recently, Dragos (9) of Romania measured hardness of ductile iron quenched and tempered after hot-pressing to 40-pct reduction at 950° or 1,050° C (1,742° or 1,922° F). Owadano (21) studied the isothermal ferritization of forged ductile iron.

In a related area, Soviet research originated with Ulitovski (29) in the 1930's has led to a process (18) for making cast iron (not ductile iron) sheet. The iron solidifies rapidly as white cast iron as it contacts casting rolls,

³Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

although the sheet center exists still molten. After passing through work rolls, it is given a graphitized-ferritize anneal to impart some ductility. Such sheet, resistant to atmospheric corrosion, can reportedly be made more cheaply than steel sheet.

Although normally unforgeable, preforms of gray cast iron have been finish-forged into flywheels by high-energy-rate forging (2). It has been demonstrated that white cast iron, also considered not workable, can also be hot forged and rolled quite successfully (10).

Objectives of the present research were to clarify conditions under which ductile iron can be hot-worked, to measure properties of worked and heat-treated materials, and to determine if various charges and different types of molds can be used without adversely affecting the workability and properties. For example, if ductile iron made by treating molten pig iron can be cast and worked into certain shapes and parts, such forms might offer an advantage over corresponding wrought steel products. These latter products require elimination of excess carbon and silicon, are energy intensive, and could be more costly. Some of the results are presented in a previous report (19).

Results show that ductile iron made with high percentages of certain pig irons and cast in sand or permanent molds can be hot-rolled and upset-forged between 1,550° and 1,950° F (843° and 1,066° C). Effects of composition, structure, reduction, and temperature on the workability of ductile iron are discussed. Properties depend on factors such as composition, type of mold, reduction, cooling rate, and heat treatment. Heavily worked material has relatively high hardness and strength, but low ductility and impact resistance, particularly in the transverse direction of sheet. Ferritize-annealing (also called ferritizing-annealing) reduces strength and improves ductility and impact resistance, but substantial anisotropy, resulting from directional graphite nodule deformation, remains. Cross-rolling can reduce anisotropy.

EXPERIMENTAL PROCEDURE

Heats

Heats were melted from four charge types (table 1). The A-type consisted wholly of electrolytic iron, carbon powder, and ferroalloys, with no pig iron. The B-type contained 70 wt-pct pig iron, half a special-low phosphorus pig iron (6) and half a low-phosphorus grade,⁴ and the C-type contained 65 pct of in Bessemer-grade foundry pig iron. The D-type contained 70 pct of a basic grade of steelmaking pig iron (table 2), and the E- and F-types were made with 85 and 95 pct of the basic grade of pig iron, respectively. Heats were constituted to have nominally 2.2 to 2.6 pct Si, carbon equivalent (CE) of 4.1 to 4.5 (eutectic pig iron), with 0.4 pct Ni in some heats. These are common ranges for ductile iron.

⁴Hereafter, this combination will be called LP pig iron.

TABLE 1. - Composition of heats

Heat No.	Analysis, wt-pct							CE ^a
	C	Si	Mn	Ni ¹	S	P	Mg	
NO PIG IRON								
52-A.....	3.34	2.46	0.58	0.37	0.002	0.015	0.035	4.17
53-A.....	3.22	2.46	.29	0	.005	.016	.030	4.04
59-A.....	3.33	2.40	.57	0	.004	.010	.030	4.13
63-A.....	3.48	2.25	.28	0	.005	.015	.030	4.24
67-A.....	3.43	2.38	.55	0	.003	NA	.035	4.23
68-A.....	3.44	2.44	.30	.41	.004	.020	.040	4.26
70 PCT LP PIG IRON								
54-B.....	3.52	2.27	0.28	0	0.009	0.024	0.030	4.29
58-B.....	3.46	2.72	.55	0	.009	.019	.035	4.37
64-B.....	3.70	2.09	.26	0	.010	.014	.040	4.40
66-B.....	3.67	2.16	.55	0	.008	.020	.035	4.40
70-B.....	3.46	2.50	.25	.40	.007	.017	.050	4.30
70 PCT BESSEMER PIG IRON								
62-C.....	3.55	2.22	0.55	0	0.016	0.035	0.035	4.30
65-C.....	3.42	2.27	.56	0	.017	NA	.035	4.18
70 PCT BASIC PIG IRON								
81-D.....	3.58	2.45	0.52	0	0.008	0.074	³ 0.052	4.42
82-D.....	3.52	2.30	.55	0	.025	.070	.034	4.31
85 PCT BASIC PIG IRON								
97-E ⁴	3.70	1.73	0.48	0	0.008	0.080	³ 0.030	4.31
98-E.....	3.43	2.22	.60	0	.007	.097	³ .040	4.20
95 PCT BASIC PIG IRON								
A01-F.....	3.54	2.54	0.73	0	0.009	0.10	³ 0.039	4.42
A02-F ⁴	3.36	2.16	.56	0	.010	.10	³ .048	4.11

NA Not analyzed.

¹Zeros indicate that no nickel was added.

²Carbon equivalent = pct C + 1/3 (pct Si + pct P).

³Nodulized with magnesium-impregnated coke; others nodulized with magnesium-ferrosilicon.

⁴Oxidizing slag added.

TABLE 2. - Pig iron analysis

Pig iron grade ¹	Analysis, wt-pct				
	C	Si	Mn	S	P
Special-low-phosphorus...	4.3	0.87	0.23	0.016	0.014
Low-phosphorus.....	4.0	2.12	.25	.017	.019
Bessemer.....	4.1	1.91	.92	.035	² .064
Basic.....	4.2	1.51	.84	.030	.10

¹First three pig irons had traces of Ca, Co, Cr, Cu, Mg, Ni, Ti, and V; basic grade had also Al, Sn, Zn, but no Co.

²Marketed as Bessemer grade, but analyzed less than 0.076 pct P minimum listed in ASTM Specification A43-67 (6).

The 115- to 120-pound heats were induction melted in MgO crucibles. Temperature was monitored with platinum versus platinum-rhodium thermocouples in protection tubes, and CE with a Tectip⁵ apparatus. Manganese and silicon were added as ferroalloys. Most heats were nodularized by tapping over magnesium-ferrosilicon in a preheated ladle. Nickel was added as Ni-Mg nodulizing alloy. All but one heat made with the basic pig iron (heat 82-D) was nodulized by plunging Mag-Coke⁶ just before tapping. A small amount of cerium or mischmetal was added to all heats to control the effects of trace elements on nodulization (residual 0.006 to 0.012 pct Ce). All heats were ladle inoculated with ferrosilicon; castings were mold inoculated with a few grams of powered ferrosilicon.

When melting heats 97-E and A02-F, ingredients (2-1/2 pct of charge weight) for an oxidizing slag, consisting of a minus 40-mesh mixture of FeO (3 parts), CaO (1 part) and CaF₂ (1 part), were stirred into the melt while holding at 2,325° to 2,375° F (1,274° to 1,301° C) for ten min. The slag was removed before heating to the tapping temperature. The additions decreased the silicon and manganese substantially (table 1); the phosphorus and sulfur were relatively unchanged.

Heats were tapped near 2,820° F (1,549° C), and casting started at about 2,595° F (1,424° C).

Castings

For rolling-stock, horizontal green-sand slabs and vertical permanent mold-ingot slabs (hereafter referred to as ingots) were cast. The green-sand slabs were 7 inches long by 6-1/4 inches wide by 1 inch thick. The cropped permanent mold ingots were about 14 inches long by 3-1/2 inches wide by 1-4/5 inches thick. Each type provided two rolling slabs about 7 inches wide by 3-1/2 inches long. For hot-forging, 3-inch-diameter permanent mold ingots 8 inches tall were cast, which provided machined 2-1/2-inch diameter by billets⁷ 2 inches tall. Small billets for cold-forging, 3/4 inch diameter by 3/4 inch tall, were machined from sand castings. The cast iron permanent molds were coated with silica wash and torched briefly before casting (big end up) to demoisurize. Standard 1-inch keel-block molds (core sand) were cast from some heats. Gammagraphs showed that most permanent mold ingots yielded 90 pct or more below the pipe. Surface defects were ground out before rolling.

Rolling

The slabs were rolled on a two-high mill at 1,550°, 1,750°, or 1,950° F at a speed of 175 ft/min, in one direction only, turning the slabs over and

⁵Reference to specific brand names is made for identification only and does not imply endorsement by the Bureau of Mines.

⁶Commercial nodulizer consisting of magnesium-impregnated foundry coke (45 pct Mg).

⁷The cast starting material for forging is referred to as a billet, although it should be realized that in steelmaking terminology, forging billets have often undergone extensive prior rolling.

reheating between passes. The roll diameter was 7-3/4 inches for rolling of the sand castings and 7 inches for rolling of the permanent mold ingots. Reheat time was 30 min to 70-pct total reduction and 20 min thereafter. At 40- and 70-pct reduction, the materials were air-cooled and specimens sectioned; sheet rolled at 1,950° F was sandblasted to remove encrusted oxide before rolling further. At 90-pct reduction, the 0.10-inch sheet from sand-cast slabs and 0.18-inch sheet from permanent mold castings⁸ were air-cooled and sandblasted.

Reduction per pass was varied according to a consistent schedule based on the thickness, temperature, and capacity of the 25-hp mill. To 40-pct reduction, the reduction per pass was 6 to 10 pct; from 40- to 90-pct reduction, it was 10 to 20 pct. Special rolling beyond 90-pct reduction, rolling with heavy reduction per pass, and cross-rolling are described briefly with the results.

Forging

The billets were upset-forged at 1,550°, 1,750°, or 1,950° F by striking repeatedly with a 1,000-pound pneumatic hammer forge. The usual procedure was to forge from 2 to 1.2 inches thick (40-pct reduction), reheat 30 min, and forge to 0.6 inch (70-pct), reheating for 20 to 30 min, depending on thickness. One group was forged to 70-pct reduction at 1,750° F without reheating. Selected billets were forged to 80-pct reduction. Several billets were forged to 0.3 inch (85-pct) for tensile testing. Completed forgings were air-cooled. The small billets were upset-forged cold (room temperature) in successive reductions of about 10 pct of the initial height.

Heat Treatments

Before hot-working, the PMC ingots were heated in air for 4 hours at 1,750° F to decompose primary cementite (Fe_3C), cooled slowly to form a ferritic matrix for easier sectioning, and sandblasted. Specimens for evaluation of properties of wrought materials were ferritize-annealed in helium by heating 3 hours at 1,650° F (900° C); cooling to 1,275° F (690° C) in 3 hours and holding 6 hours; and furnace-cooling. Special heat treatments are described with the results.

Hardness

Rockwell and Brinell (3,000 kg) hardness tests were made on ground surfaces. Average values were calculated for four or more indentations. The Rockwell A-scale test was chosen for worked material because some sections become too thin to sustain the Brinell load; the Rockwell C-scale test was used on specimens of the hard as-cast PMC ingots, some of which cracked under the Brinell load.

⁸ Hereafter, material from sand castings is referred to as SC and that from permanent mold castings as PMC.

Tensile Tests

Tensile specimens for wrought materials were sheet-type (5) having a 2-inch gage length. The reduced section width was 1/2 inch for the 0.10-inch sheet and 1/4 inch for thicker materials. The tests were made on an Instron machine using a strain rate of 0.02 in/in per min to yield and 0.2 in/in per min thereafter. Normally, 16 specimens were tested from a sheet, four each longitudinal and transverse⁹ for the as-rolled conditions, and four each for the ferritize-annealed condition. Keel-block leg specimens (two per casting), standard 1/2 inch diameter (5) were tested on a Tinius Olsen machine at a 4,800-lb/min load rate to yield. Tensile strength, 0.2-pct offset yield strength, and percentage elongation were calculated.

Impact Tests

Impact tests were made on PMC material rolled to 70-pct reduction (0.54 inch). From each plate, four each as-rolled L and T specimens were machined, and an equal number of ferritize-annealed specimens. Specimens were unnotched ASTM type (5) 2.165 inches long and 0.394 inch square. The Charpy tests were made at about 75° F (24° C). Impacts were directed normal to the rolling plane.

Damping Capacity

Specific damping capacity (SDC) was measured with a torsion pendulum designed and constructed at the Rolla Research Center (24). The values represent duplicate tests on duplicate specimens of as-cast keel blocks (1-inch), as-rolled specimens (70-pct reduction at 1,750° F), ferritize-annealed specimens of each, and, for comparison, steels of 18 and 45 points carbon (0.18 and 0.45 pct C) and gray cast iron. The SDC tests were made on shouldered (3/8-inch-diameter) specimens approximately 4-1/2 inches long, and having a 2-1/2-inch gage length and a 3/16-inch reduced diameter.

Other

The chemical analyses and microscopy were essentially conventional. Carbon was determined from pin castings, and other elements were determined from drillings. Microscopy specimens were polished with diamond abrasive and etched in nital. Worked materials were sectioned to examine the region normal to the thickness. For micrographs presented of rolled materials, the rolling direction corresponds to the vertical page direction for L specimens; for T specimens, it is normal to the page.

RESULTS

Microstructures of Castings

The microstructures of two SC rolling slabs are shown in figure 1. Because of the higher manganese and phosphorus from the basic pig iron, heat 82-D (fig. 1B) contains more pearlite, but some ferrite (light) remains.

⁹Hereafter, L refers to longitudinal and T to the transverse sheet direction.

Reflecting the faster solidification, the as-cast structures of PMC ingots (fig. 2A) have higher eutectic cell and nodule count, smaller nodules, more pearlite than those of sand castings (fig. 2C) of similar composition,

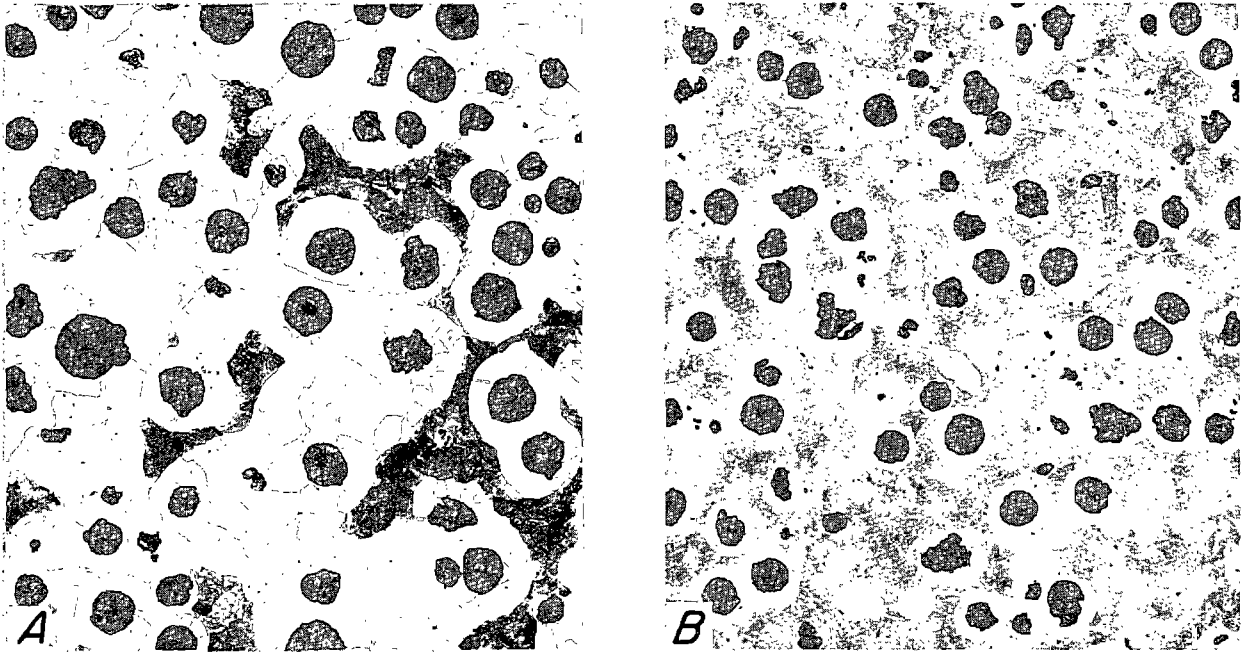


FIGURE 1. - Microstructures of sand-cast rolling slabs. *A*, Heat 64-B; *B*, heat 82-D. As-cast, X 100.

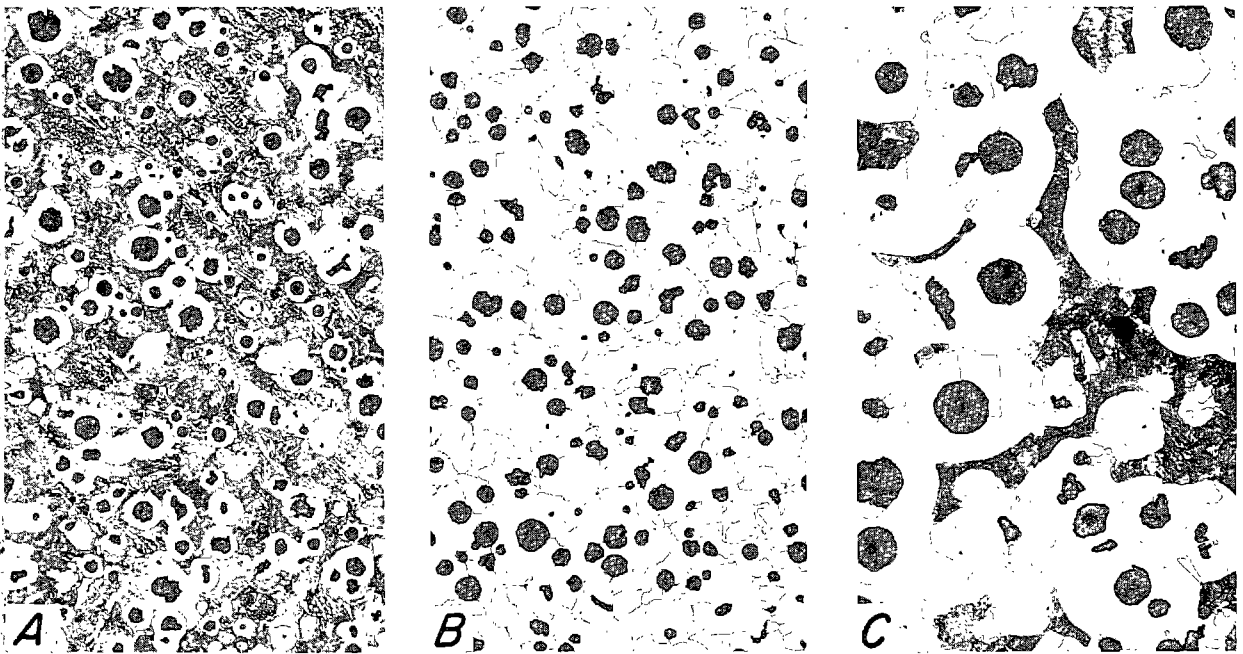


FIGURE 2. - Microstructures of permanent mold ingot and sand casting from same heat. Heat 54-B. Permanent mold ingot. *A*, As-cast; *B*, heated at 1,750° F and furnace-cooled; and *C*, sand-cast keel block. X 100.

and also primary cementite (light, acicular). Heating for 4 hours at 1,750° F and furnace-cooling slowly (fig. 2B) decomposed the cementite in PMC ingots and ferritized the matrix. Further tests showed that heating for only about 1 hour at 1,750° F could decompose the cementite. The period, which depends on section size and composition, can be part of the preheat for working. The nodule size (4) averaged No. 5 (0.08 mm) for SC materials and No. 6 (0.04 mm) for PMC ingots; the nodule count per square millimeter (13) averaged 50 to 75 and 100 to 125, respectively.

Hardness of Castings

Hardness varied substantially depending on type of casting, composition, and condition. Sand castings ranged from Brinell hardness No. (BHN) 149 to 232, with the higher values reflecting factors such as increased pearlite from higher manganese or the presence of nickel. The as-cast PMC ingots with primary cementite ranged between Rockwell-C 30 and 47; after heat treatment, the hardness dropped to between BHN 147 and 169, reflecting variable amounts of ferrite hardeners such as silicon and nickel.

Rollability

The rollability of SC slabs is coded in table 3. Rollability was better at 1,750° and 1,950° F, although all slabs were rolled to 90-pct reduction at 1,550° F. The reason for the severe cracking of the SC slabs from heats 82-D and A01-F during rolling at 1,950° F is not evident from the microstructures or chemical analyses. Sulfur was high in 82-D (which could be due to trapped sulfides) but not in A01-F (table 1). One heat was nodularized with one agent and one with the other. The fact that PMC ingots from the same heats were rolled at 1,950° F without cracking indicates that the behavior is related in some manner to the slower cooling of the sand castings. Precise interpretation must await more detailed studies. At 1,750° F, only one heat exhibited minor cracking. The two worst results at 1,550° F, with both edge and surface cracking, occurred for 67-A and 68-A, heats made without pig iron. Although these heats had higher manganese than some, or nickel (table 1), the increased cracking cannot be attributed directly to the main composition since similar heats made with pig iron cracked less. Pig irons introduce various trace impurities that can affect factors such as graphite nucleation, cell count, and gas content (33). In the present study, heats with pig iron generally had higher nodule count and better nodule distribution. An example of sheet rolled from SC slabs at the three temperatures is shown in figure 3 (leading end sectioned).

TABLE 3. - Rollability¹ of sand castings
rolled to 90-pct reduction

Heat No.	Rolling temperature, ° F		
	1,550	1,750	1,950
63-A.....	b	a	a
67-A.....	c,x	a	b
68-A.....	b,x	b	b
64-B.....	b	a	a
66-B.....	a	a	a
70-B.....	b	a	b
65-C.....	b	a	a
81-D.....	b	a	a
82-D.....	b	a	d,x ²
97-E.....	b	b	b
98-E.....	c	b	a
A01-F.....	c	b	d,x ²
A02-F.....	b	b	b

¹Rollability code: a = essentially no cracks; b = edge cracks <1/4 inch; c = edge cracks 1/4 to 1/2 inch; d = edge cracks >1/2 inch; x = surface cracks.

²Rolling stopped at 40-pct reduction.

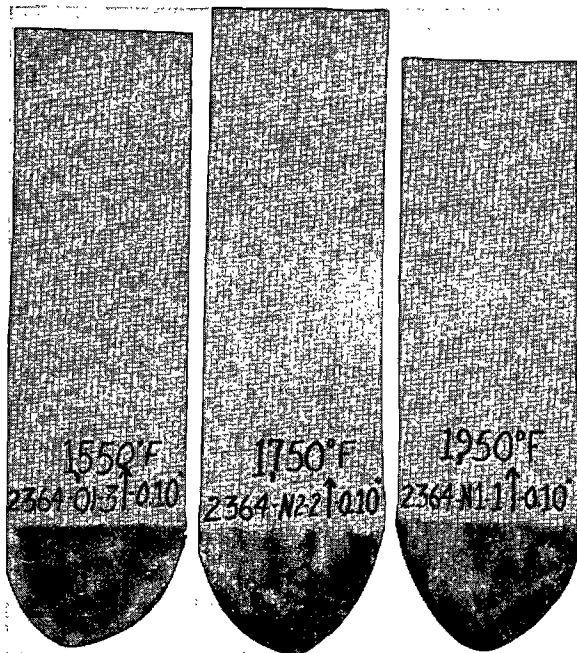


FIGURE 3. - Sheet rolled from sand-cast slabs to 90-pct reduction at 1,550°, 1,750°, and 1,950° F. Heat 64-B. Sand-blasted except tailing end.

Table 4 lists the rollability coding for PMC slabs. These slabs also rolled without cracking seriously at 1,750° and 1,950° F, but they displayed poorer rollability at 1,550° F, and most of the initially thicker slabs tended to "alligator" at the leading end after 70- to 85-pct reduction. The "alligating" would probably be alleviated with different ratios of roll diameter to sheet thickness, but the most straightforward solution is to roll at higher temperature. The increased cracking at 1,550° F in comparison with SC material is evidently related to the lesser fracture path between the smaller and more numerous nodules, coupled with the decreased plasticity at the lower temperature. This indicates that there must be optimum ranges of nodule size and distribution that will produce optimum workability at the lower working temperatures.

TABLE 4. - Rollability¹ of permanent mold castings rolled to 90-pct reduction

Heat No.	Rolling temperature, ° F		
	1,550	1,750	1,950
53-A.....	c	a	a
59-A.....	d,x	a	a
54-B.....	c,x	a	a
58-B.....	d,x	b	a
62-C.....	c	a	a
81-D.....	c,x	b	a
82-D.....	c	b	a
97-E.....	c	b	a
98-E.....	c	b	a
A01-F.....	c	b	a
A02-F.....	c	b	a

¹Rollability code: a = essentially no cracks; b = edge cracks <1/4 inch; c = edge cracks 1/4 to 1/2 inch; d = edge cracks >1/2 inch; x = surface cracks.

The results for both SC and PMC materials show that there is considerable latitude in charge and composition for rolling stock. Some structural and compositional effects will be discussed further with the forgeability results.

In further work, PMC slabs from heats 54-B and 58-B were rolled to 96-pct reduction (to 0.07 inch) at 1,950° F without cracking.

Small SC slabs (2-1/2 by 2-1/2 inches) from heat 65-C were cross rolled with 20-pct reduction per pass to 90-pct total reduction at 1,950° F and to 80 pct at 1,750° F without cracking. This shows that ductile iron can be cross rolled as a means of reducing the anisotropy resulting from directional nodule deformation.

To check on effects of reduction per pass, small SC slabs (64-B, 66-B) were rolled at 20-pct or at 40-pct reduction per pass to 92-pct total reduction at 1,750° F and at 1,950° F. With 20-pct reduction per pass, little cracking occurred at either temperature. However, at 40-pct reduction per pass, severe cracking started at both temperatures when rolling from 65- to 79-pct total reduction, showing that reduction rate becomes important at heavier reductions.

A few instances were also noted where surface cracks would develop if initial passes were exceptionally large, especially at 1,550° F.

Microstructures of Rolled Materials

The microstructures of a SC slab (64-B) as-rolled to various total reductions at 1,750° F (fig. 4) illustrate the nodule deformation as rolling progresses. The nodules are enveloped in ferrite, and the remaining matrix is

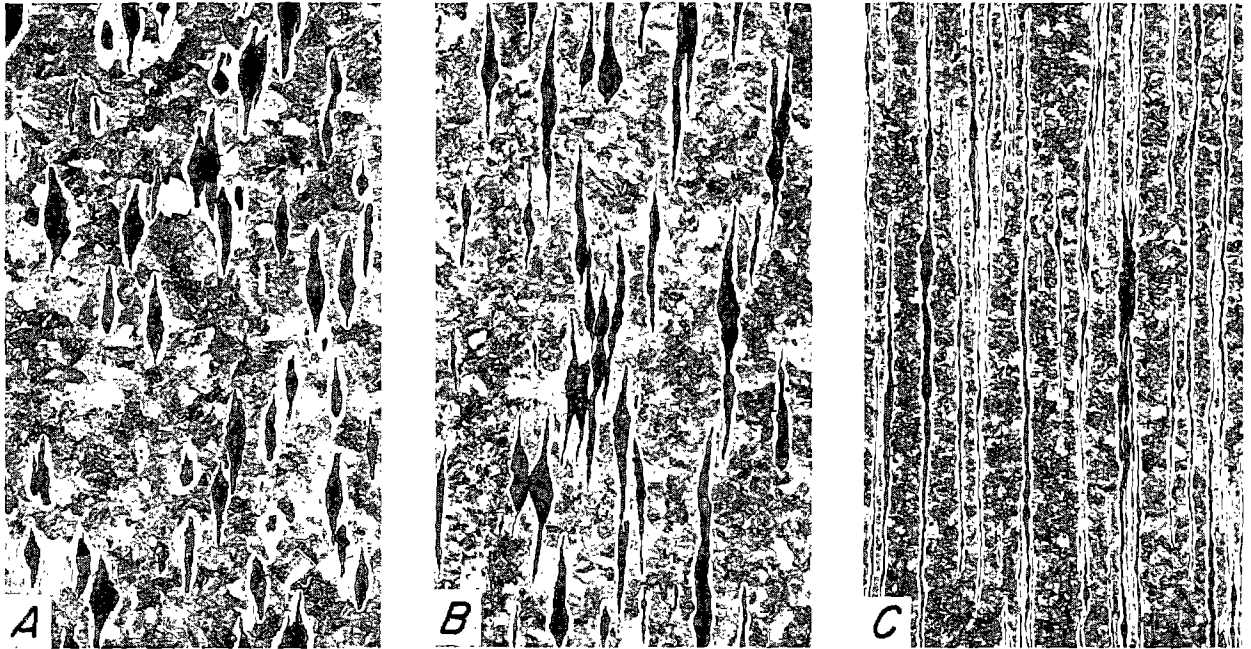


FIGURE 4. - Microstructures of ductile iron rolled to 40-pct *A*, 70-pct *B*, and 90-pct *C*, reduction at 1,750° F. Heat 64-B. As-rolled from sand-cast slabs, longitudinal, X 100.

pearlite. The ferrite forms during cooling by diffusion of matrix carbon to the nodules. Close examination reveals that some nodules deform by peeling off outer layers of graphite.

Structures of the same heat (fig. 5) rolled at 1,550° and 1,950° F show that the ferrite morphology differs. The ferrite envelopes formed after rolling at 1,950° F (fig. 5B) are similar, although thinner than those for rolling at 1,750° F (fig. 4C). However, for rolling at 1,550° F (fig. 5A), substantial ferrite appears as dispersed particles, many separated from the graphite. This is attributed to the temperature of the thin material cycling below and above the lower critical temperature (8) during final rolling. Below the lower critical, austenite becomes unstable and ferrite can form. When reheated to 1,550° F, between the lower and upper critical, the ferrite is evidently incompletely redissolved, and is thus deformed and dispersed in the succeeding pass. This ferrite morphology, not noted in the thicker PMC materials, apparently had no marked effect on rollability, insomuch as the SC sheet could usually be finish-rolled at 1,550° F with less cracking than the PMC sheet. It is, however, symptomatic of working where lower temperature phases come into play and plasticity is diminished. For both type castings, the amount of ferrite generally decreased with increased rolling temperature.

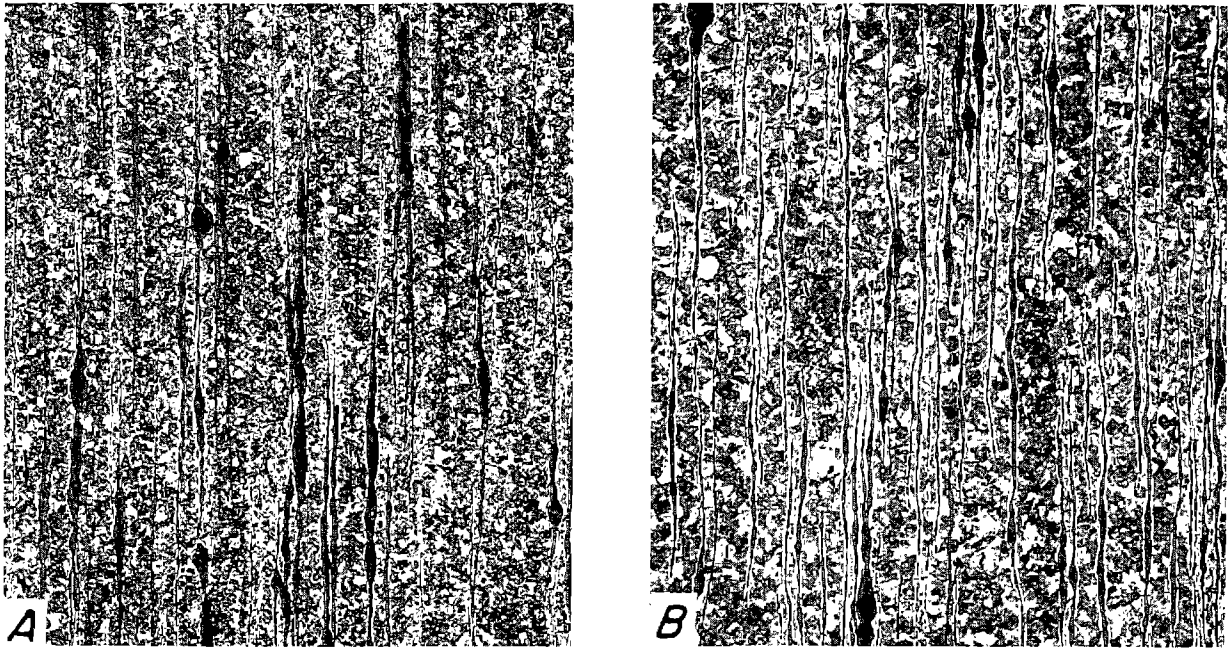


FIGURE 5. - Microstructures of sheet rolled from sand-cast slabs to 90-pct reduction at *A*, 1,550° F and *B*, 1,950° F. Heat 64-B. Longitudinal, X 100.

The microstructures of a PMC slab of similar composition (54-B) rolled to 90-pct reduction at 1,750° F (fig. 6) illustrate the closer spacing of the smaller rolled-out nodules. As-rolled, more ferrite is present because the thicker PMC material cools slower, and also the path is less for matrix carbon diffusion to the more numerous nodules. Comparison of the L and T structures (fig. 6, panels A and B) illustrate the directionally deformed nodules; C shows the structure after ferritize-annealing.

Figure 7 shows the structures (annealed) of sheet from a PMC ingot of the same heat that was rolled to 96-pct reduction at 1,950° F. The rolled-out nodules are closer together and, even with the heavy reduction, some nodules are partially intact.

Microscopic examination of cross-rolled sheet verified that the nodule morphology was essentially the same in L and T directions with respect to the last rolling pass.

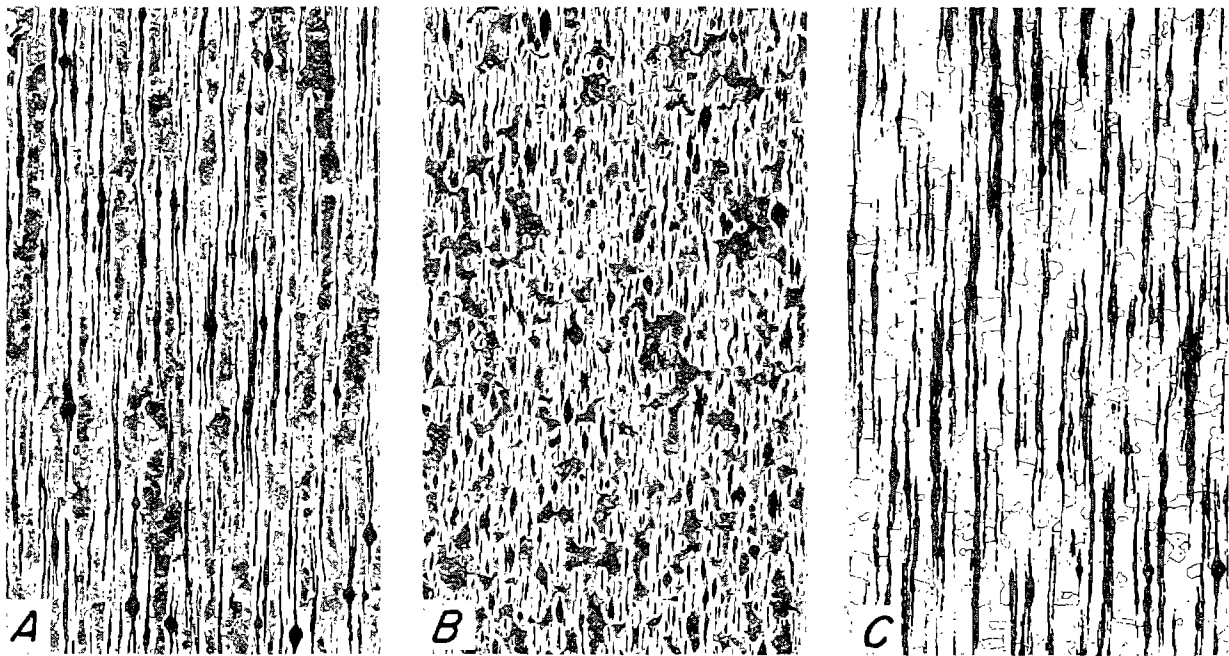


FIGURE 6. - Microstructures of sheet rolled from permanent mold ingots to 90-pct reduction at 1,750° F. Heat 54-B. *A*, Longitudinal, as-rolled; *B*, transverse, as-rolled; and *C*, longitudinal, ferritize-annealed. X 100.

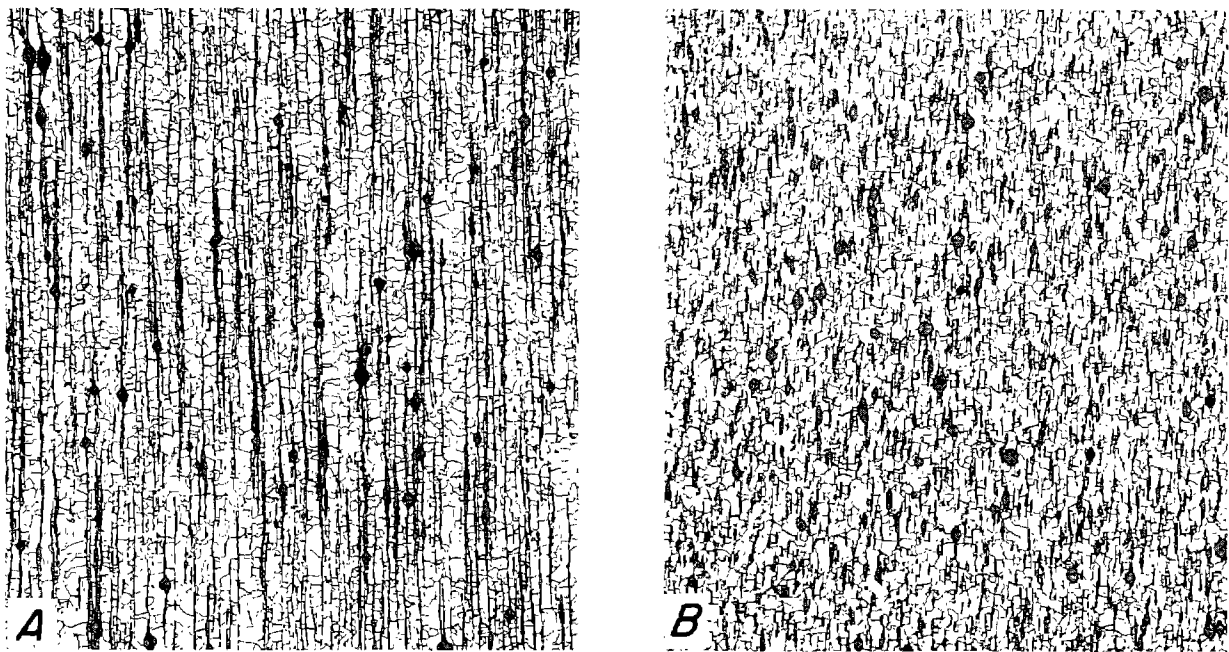


FIGURE 7. - Microstructures of sheet rolled from permanent mold ingot to 96-pct reduction at 1,950° F. Heat 54-B. *A*, Longitudinal; *B*, transverse. Ferritize-annealed, X 100.

Forgeability

The forgeability is coded in table 5. As for rolling, forgeability improved with increasing temperature. At 1,950° F, only one billet cracked somewhat when forged to 70-pct reduction in height. At 1,750° F, three forgings cracked, one severely. At 1,550° F, 5 of the 10 billets forged to 70-pct reduction cracked extensively, whereas the others had essentially no cracking. Because of more cooling during forging, forgeability was a little poorer when most heats were forged at 1,750° F to 70-pct reduction without reheating (not coded in table 5). All billets selected for forging to 80-pct reduction did so without cracking.

TABLE 5. - Forgeability¹ of billets upset-forged to 70-pct reduction

Heat No.	Forging temperature, ° F		
	1,550	1,750	1,950
52-A.....	d	(²)	a ³
63-A.....	c	a	a ³
67-A.....	c	b	a
68-A.....	d	d	b
64-B.....	a	a ³	a ³
66-B.....	a	a ³	a
70-B.....	d	b	a
65-C.....	a ³	a ³	a ³
81-D.....	a	a	a
82-D.....	a	a	a
97-E.....	a	a	a
98-E.....	a	a	a
A01-F.....	a	a	a
A02-F.....	a	a	a

¹Forgeability code: a = essentially no cracks; b = edge cracks <1/4 inch; c = edge cracks 1/4 to 1/2 inch; d = edge cracks >1/2 inch.

²Not rolled.

³Also forged to 80-pct reduction without cracking.

The relative ease of forging should relate generally to the rollability, although the nodules are lengthened as well as flattened during rolling. From the standpoint of composition, the three forgings that cracked most severely at 1,550° F were from the three heats with the 0.4 pct Ni addition. The other two that cracked less severely at 1,550° F, 63-A and 67-A, were from heats made without pig iron. At 1,750° F, of the three forgings that cracked, two, 68-A (cracked severely) and 70-B, contained nickel; the forging from 68-A was also the only one that cracked at 1,950° F. Other than for nickel, which has substantial solubility in austenite, no definite correlation was noted between forgeability and the compositions represented, although the lower silicon heats generally produced good results. If present over a wider range than the 1.7 to 2.5 pct Si in the billets forged, silicon would be expected to influence workability since it is soluble in austenite, is a strong graphitizer, and

raises the lower critical temperature. Manganese between 0.3 and 0.7 pct had little effect. All of the billets from heats made with basic pig iron, even for 95 pct of the charge, forged without cracking. The higher phosphorus in these heats (0.07 to 0.10 pct) and high sulfur in 82-D (0.025 pct) produced no adverse effect. As was the case for rolling, heats with pig iron forged better than those without, and castings with obviously poor nodularity had poor forgeability, although some vermicular graphite had little effect.

The hot-forging sequence is illustrated in figure 8.

Small billets from heats 64-B, 66-B, and 70-B were upset-forged cold with successive 10-pct reductions of the starting height. Three or four billets from each heat were forged in both the as-cast and ferritize-annealed conditions. For both conditions, the billets were forged to 50-pct reduction without cracking. The cracking usually occurred at 60-pct reduction, but

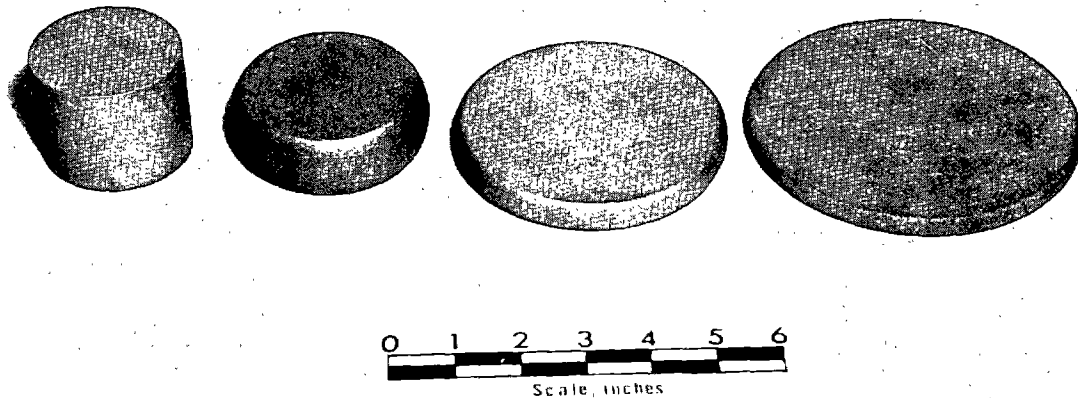


FIGURE 8. - Forging sequence. Two-inch-high starting billet (left) forged to 40-pct, 70-pct, and 80-pct reduction.

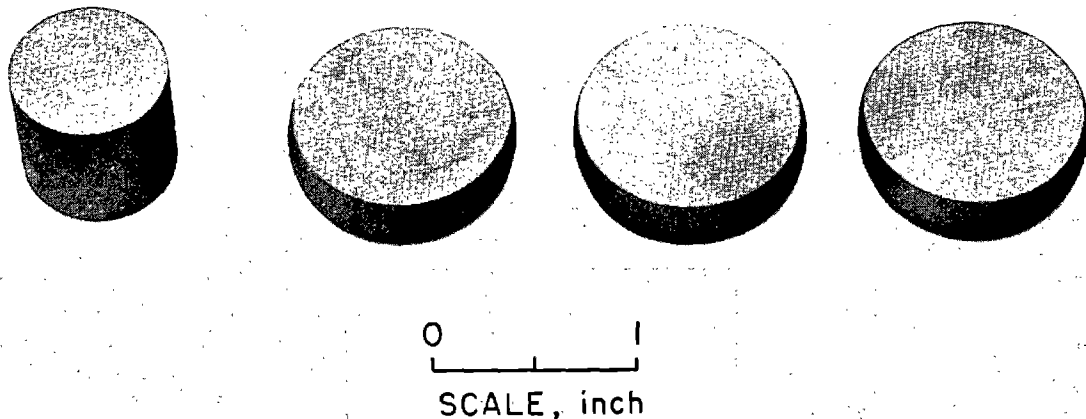


FIGURE 9. - Ductile iron billets cold-forged to 50-pct reduction. (Starting billet on left.)

three did not crack until reduced 70 pct. Figure 9 shows a starting billet and three billets cold-forged to 50-pct reduction.

Examples of the microstructures of a billet forged to 70-pct reduction at 1,750° F and a billet forged cold to 60-pct reduction (not annealed before forging) are shown in figure 10, panels A and B, respectively. The hot-forged billet was from PMC material, and the cold-forged billet was from SC material (larger nodules).

Hardness and Tensile Properties of Wrought Materials

Examples of the hardness of SC slab and a PMC ingot of similar composition as a function of rolling temperature and percent reduction are shown in figure 11. In figure 11B, the as-cast hardness is that of the keel-block casting. The general behavior is similar for both, although, for a given temperature and reduction, the SC material is thinner than the PMC material, and therefore cools faster and develops a higher pearlite-to-ferrite ratio. When rolling to 40-pct reduction, the hardness increases because cooling is faster than for the castings, permitting more pearlite to form. For rolling to 70- and 90-pct reduction, hardness becomes very dependent on rolling temperature, resulting from several factors. As rolling temperature decreases, more graphite and ferrite can form because of decreased carbon solubility in austenite. This, coupled with the lessening graphite spacing and carbon diffusion path for graphite deposition on the nodules, causes the hardness to tail off at 1,750° and 1,550° F at 70- and 90-pct reduction even though the

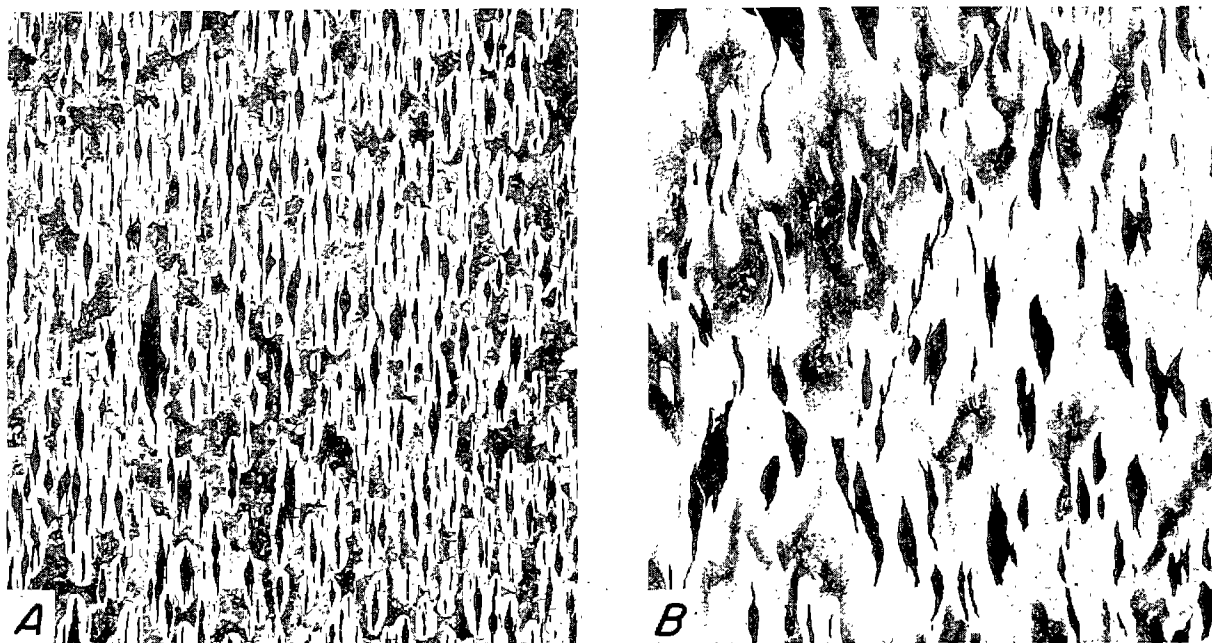


FIGURE 10. - Microstructures of hot- and cold-forged billets. Heat 66-B. A, Forged to 70-pct reduction at 1,750° F; B, forged cold to 60-pct reduction. X 100.

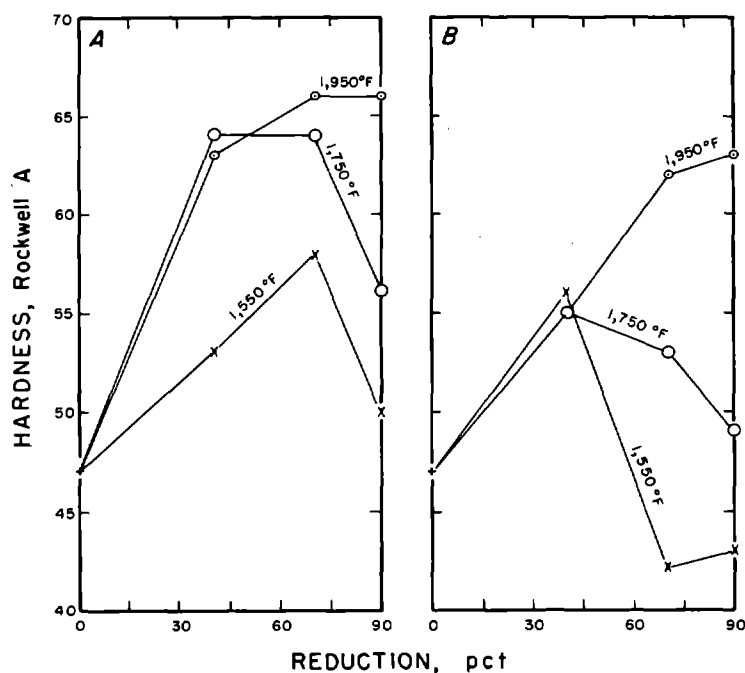


FIGURE 11. - Hardness as a function of rolling temperature and percent reduction. A, Heat 64-B, sand-cast slab; B, heat 54-B, permanent mold ingot.

sheet becomes thinner and cools faster. Pearlite formed when cooling from higher temperatures is also finer and harder. The hardness for different compositions generally coincided with the relative presence of pearlite stabilizing elements such as manganese, and ferrite strengtheners such as silicon and nickel. Other factors equal, the hardness and strength of ductile iron decreases with increased carbon (normally ~3.4 to 4.4 pct).

Ferritize-annealing significantly reduces hardness. For example, the hardness of the sheet of heat 64-B (see fig. 11) rolled to 90-pct reduction between 1,550° and 1,950° F dropped after annealing from Rockwell-A 50 and 66 to only Rockwell-A 30 and 38,

respectively. Annealed hardness still reflected the effect of rolling temperature. Hardness data for all rolled materials that were tensile tested are listed in appendix A.

Selected tensile properties are listed in table 6 for sheet rolled from SC and PMC slabs to 90-pct reduction between 1,550° and 1,950° F; other selected data are plotted in figures 12 and 13 to graphically illustrate the relative behavior as a function of type of casting, orientation, rolling temperature, and whether or not annealed. A number of factors affect behavior, which may be characterized as follows. For as-rolled sheet, strength is high and elongation is low. Strength, and to a lesser extent elongation, increase with rolling temperature. The L specimens exhibit higher strength and elongation than T specimens because the stress is applied parallel to the graphite "stringers." The L and T tensile strengths differ more than yield strengths. For otherwise equivalent conditions (percent reduction, temperature, etc.), the thicker PMC materials develop less pearlite and lower strength than the SC materials, but elongations are not greatly different. As noted for the hardness, compositional variations that increase pearlite and harden ferrite increase strength. Ferritize annealing diminishes anisotropy in strength but anisotropy in elongation remains high. The different graphite distribution leads to higher strengths for the annealed sheet rolled from PMC slabs, in comparison to that rolled from SC slabs, which is converse to the as-rolled behavior where the relative amount of pearlite was a dominant factor. Annealed tensile

properties, both strength and elongation, also improved with increasing rolling temperature. As the relative amounts of ferrite and graphite become essentially constant for a given heat, regardless of rolling temperature, this must result from factors such as small differences in ferrite grain size and secondary graphite deposition from decomposing pearlite resulting from the varied rolling temperature before annealing.

TABLE 6. - Tensile properties of sand-cast and permanent mold materials rolled to 90-pct reduction and ferritize-annealed

Heat No.	Rolling temp., ° F	Orientation	As-rolled			Ferritize-annealed		
			Tensile strength, psi	Yield strength, psi	Elongation pct	Tensile strength, psi	Yield strength, psi	Elongation pct
SAND-CAST MATERIAL ¹								
66-B....	1,550	L	108,400	84,800	3	53,100	39,300	7-1/2
		T	72,400	67,500	1-1/2	41,400	36,100	2-1/2
	1,750	L	148,300	105,500	4	56,300	37,800	12
		T	88,100	76,600	2	43,400	36,000	3
	1,950	L	157,800	113,100	3-1/2	61,000	41,600	15
T		118,100	98,000	2	50,600	38,600	4-1/2	
81-D....	1,550	L	95,700	75,600	3	56,500	42,600	9
		T	70,800	65,200	1	42,400	37,500	3
	1,750	L	125,000	94,900	2-1/2	58,600	43,900	9-1/2
		T	76,500	76,200	1	43,100	38,400	2
	1,950	L	164,300	114,100	4	67,300	48,300	13-1/2
		T	117,500	103,900	1	54,800	43,900	4
PERMANENT MOLD MATERIAL ²								
58-B....	1,550	L	68,200	60,100	2-1/2	56,000	46,600	3
		T	57,700	56,500	1/2	48,600	45,700	1-1/2
	1,750	L	105,800	74,200	5	69,100	49,200	13
		T	77,100	65,700	1-1/2	56,400	47,400	3
	1,950	L	125,000	78,100	5-1/2	67,500	49,700	13-1/2
T		97,700	74,100	2-1/2	59,400	48,300	4	
81-D....	1,750	L	120,700	77,400	6-1/2	63,500	46,200	13
		T	85,900	70,800	2	52,300	42,100	3-1/2

¹At 90-pct reduction, 0.10 inch thick.

²At 90-pct reduction, 0.18 inch thick.

For comparison with the sheet properties in figure 13, the as-cast tensile properties for heat 54-B (keel block) were 65,200 psi tensile strength, 42,000 psi yield strength, and 17-1/2-pct elongation. Tensile data for rolled materials not listed in table 6 are given in appendix B. The sheet from heat AO2-F, which was made with 95-pct basic pig iron and had a deoxidizing slag addition, had the best overall tensile properties from the standpoint of yield strength and elongation combinations.

Tensile tests on material from heats 64-B and 66-B rolled to only 70-pct reduction at 1,750° F (see appendix B, table B-3) showed that, as-rolled, anisotropy in strength was less than when rolled to 90-pct reduction (fig. 10, table 6, table B-1). Elongations were relatively unchanged. After annealing,

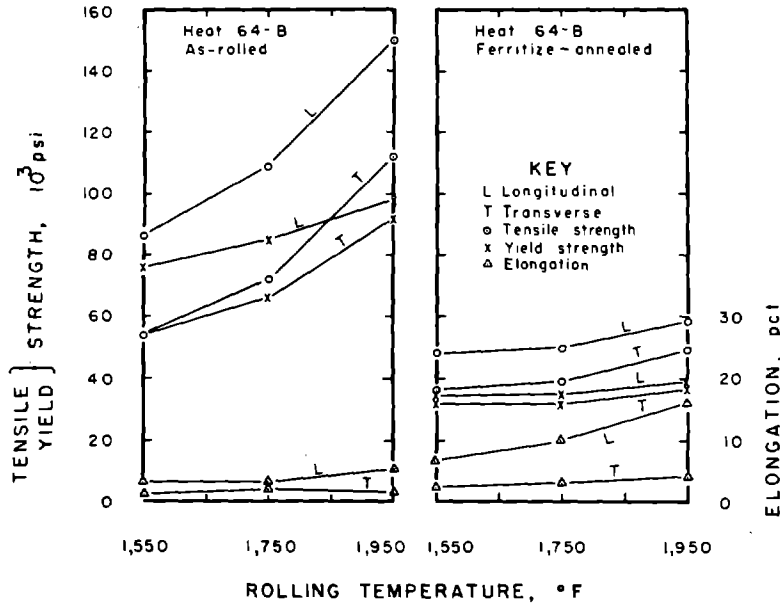


FIGURE 12. - Tensile properties of sheet rolled from sand-cast slabs to 90-pct reduction. Heat 64-B. A, As-rolled; B, ferritize-annealed.

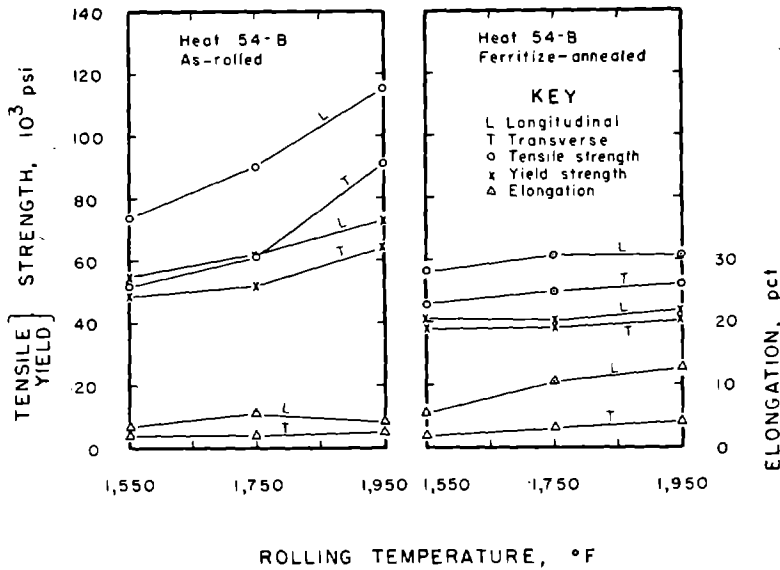


FIGURE 13. - Tensile properties of sheet rolled from permanent mold ingots to 90-pct reduction. Heat 54-B. A, As-rolled; B, ferritize-annealed.

materials rolled to 70-pct reduction had higher tensile strengths and less anisotropy than those rolled to 90-pct reduction. Yield strengths changed but little. Elongations, however, increased to about double those for the sheet rolled to 90-pct reduction and annealed, reaching about 20 pct for L specimens. Nonetheless, anisotropy persisted in view of the fact that T elongations increased to only 7 pct for 64-B and 5 pct for 66-B.

Tensile properties were determined for an annealed sheet that was cross-rolled to 90-pct reduction at 1,950° F. The specimens were subsize (0.25-inch-wide reduced section, 1-inch gage length) so that both L and T sheet directions (with respect to last rolling pass) could be tested from the same sheet. In one direction, tensile strength averaged 56,800 psi, yield strength 43,700 psi, and elongation 7 pct; in the other direction, the values were 54,200 psi, 42,400 psi, and 6 pct, respectively.

For material forged to 85-pct reduction, the hardness and tensile properties also increased with hot-working temperature for both the as-forged and annealed conditions (appendixes A and B).

Impact Properties

Results of impact tests on as-rolled and ferritize-annealed specimens rolled from PMC ingots to 70-pct reduction at 1,750° F are given in table 7. The overall behavior follows a generally consistent pattern. Both as-rolled

and annealed, L specimens averaged roughly double the impact resistance of T specimens. Annealed specimens average about double that of as-rolled, L = 47 ft-lb and T = 22 ft-lb; annealed, L = 103 ft-lb and T = 45 ft-lb. The lowest values occurred for heat A01-F, apparently reflecting the relatively high carbon, silicon, and manganese content from this heat made with 95 pct basic pig iron. However, heat A02-F, made with the same amount of basic pig iron but with the deoxidizing slag addition, had properties consistent with the overall averages. Annealed specimens from heats made with 85 or 95 basic pig iron averaged lower in L strength but higher in T strength. The high phosphorus in the heats made with basic pig iron produced no gross embrittlement as often occurs in castings with this much phosphorus. Annealed ferritic ductile iron castings tested similarly exhibit about 100 ft-lb for the ductile range and below 20 ft-lb for the brittle range (3, p. 390). On this basis, the annealed L specimens represent essentially fully ductile behavior, the as-rolled T specimens are approaching brittle behavior, and the others are intermediate.

TABLE 7. - Impact energies¹ of ductile iron rolled to 70-pct reduction at 1,750° F and ferritize-annealed

Heat No.	Orientation	Energy absorbed, ft-lb	
		As-rolled	Ferritize-annealed
53-A.....	L	57	114
	T	21	41
59-A.....	L	55	110
	T	18	37
54-B.....	L	55	100
	T	27	43
58-B.....	L	54	101
	T	27	47
62-C.....	L	43	109
	T	18	41
81-D.....	L	47	106
	T	25	54
82-D.....	L	45	110
	T	22	44
97-E.....	L	44	91
	T	25	53
98-E.....	L	39	93
	T	17	45
A01-F.....	L	34	92
	T	20	42
A02-F.....	L	44	104
	T	23	47

¹Charpy test at room temperature, unnotched specimen.

Damping Capacity

Results of damping capacity measurements are given in table 8 for as-cast experimental keel-block castings of ductile iron, ductile iron rolled to 70-pct

reduction at 1,750° F from PMC, ferritize-annealed material of each, and, for comparison, gray cast iron and wrought 0.18 and 0.45 pct carbon steel. The results show that the rolling enhances the specific damping capacity (SDC) of both L and T specimens, with the largest increase occurring for the L specimens. The L specimens have increased SDC of >60 pct relative to the cast material, and T specimens have increased SDC of >40 pct. The ferritize-annealing results in substantially increased SDC by conversion of the matrix to essentially all ferrite. The L specimens of ductile iron had over 2-1/2 times the SDC of the as-cast keel block, and over twice that of the annealed keel block. The annealed ductile iron rod, rolled to 94-pct reduction at 1,925° F, had somewhat lower SDC than the annealed ductile iron sheet. The as-cast gray cast iron had a SDC of about four times that of as-cast ductile iron; this results from the presence of the continuous graphite flakes of gray cast iron, which act as excellent sinks to absorb vibration. Conversely, the AISI-1018 and 1045 steels have low SDC essentially because of the absence of any free graphite to enhance absorption of vibration.

TABLE 8. - Specific damping capacity (SDC) of as-cast,¹ as-rolled,² and ferritize-annealed³ ductile iron compared with gray cast iron and steel

Material	Condition	SDC, ⁴ pct	
		10,000 psi	15,000 psi
Ductile iron..	As-cast.....	2.2	2.8
Do.....	As-rolled sheet, longitudinal.....	3.6	4.6
Do.....	As-rolled sheet, transverse.....	3.1	4.1
Do.....	Cast, ferritize-annealed.....	3.1	3.2
Do.....	Rolled sheet, longitudinal, annealed..	6.0	7.3
Do.....	Rolled sheet, transverse, annealed....	5.0	4.9
Do.....	Rolled rod, annealed.....	3.5	4.1
Gray iron.....	As-cast (ASTM-GC-40).....	9.2	--
Steel.....	AISI-1018, as-rolled.....	1.4	1.6
Do.....	AISI-1045, as-rolled.....	1.8	1.8

¹1-inch keel-block casting.

²Sheet rolled to 70-pct reduction at 1,750° F from PMC; bar rolled to 94-pct reduction in cross section at 1,925° F from continuous-cast bar.

³Heated 3 hours at 1,650° F, slow furnace-cooled to 1,285° F, held at 1,285° F, for 12 hours, and furnace-cooled.

⁴Measurements with torsion pendulum.

TRIAL DIE-FORGING TESTS

Brief trials of forging of ductile iron were made under Bureau direction at Moog Automotive, Inc., Wellston, Mo. (tie rod), A. B. Chance Co., Centralia, Mo. (guy wire anchor), and Hatebur Metalforming Equipment, Basle, Switzerland, through Girard Associates, Inc., Cleveland, Ohio (machine nuts). Although parts were forged, these trials were only partly successful, and indicated the need for more detailed evaluation of factors such as die constraint, forging reduction, and forging reduction rate.

A Bureau contract was awarded to the Forging Industry Educational and Research Foundation (26). The trials were carried out at the Columbus Forge and Iron Co. under the direction of D. E. Tilton and S. Eliot. J. W. Spret-nak of Ohio State University served as principal investigator; S. J. Kiefer and R. T. Hergegen, Jr., represented the research foundation.

Six geometries of production items normally forged in steel were selected to be forged under plant conditions. The items, a crankshaft, a cone forging (failed), a flange (failed), a trolley wheel, and large and small spools, produced a total of over 250 forged pieces. The crankshaft was forged from both bar stock and a rough-cast preform. Board hammers, gravity drop hammers, and steam hammers were used (1,500 to 3,500 pounds), and a 175-ton hydraulic press. Forging temperature, specified by the Bureau along with other basic operating variables, ranged nominally from 1,700° to 1,950° F. Heating furnace fuel was either gas or oil-gas. The starting stock was commercially continuous-cast ductile iron bar ranging from 1-1/2 to 4-1/2 inches in diameter (some ini-tially machined somewhat to required diameter). The ductile iron was nominally ASTM 65-45-12 (silicon averaged ~3 pct; typical 65-45-12 is 2.3 to 2.8 pct Si). Some castings of variable silicon content between 2 and 4 pct were supplied by the Bureau of Mines from laboratory-prepared castings for upset tests to compare effects of variable silicon on the forgeability of ductile iron relative to steel.

The forging configurations selected represented a range of forging dif-ficulty or demands of the metal as to its ability to flow without suffering ductile fracture (tearing). For the trials, changes were made to the parame-ters such as temperature, but not to the dies. Observations were made on factors such as the ability to fill the die cavity and the presence or absence of cracks; effects of heating temperature, forging rate, and heating atmosphere; and scaling behavior, shearing of stock, and trimming of flashing.

Two of the forging designs, a cone forging and a flange forging, cracked early in the forging sequence and trials were discontinued. The other forgings were carried out until essentially the final configurations were reached. Excellent results were achieved in forging of the crankshaft from the rough preform, although the part was also forged about as well from the bar stock, but with more blows required. Laboratory evaluation of the microstructure, hardness, and deformation characteristics were carried out at Ohio State University. The experiments, results, and conclusions are given in detail in the final contract report (26). Only some of the more significant findings will be discussed herein.

Graphite nodules flowed readily under deformation and eventually became continuous stringers. The degree of deformation can be characterized by the asperity ratio of the graphite particles. The hardness of deformed graphite particles indicates increasing graphite-particle interaction as deformation proceeds. Fractures in ductile iron are judged to occur by either of the two basic modes of (1) cavities containing graphite particles by continuing plastic flow as in edge cracking (ductile fracture mechanism), or (2) the activation of a shearing instability in the directions of pure shear (zero extensional strain).

Ductile iron billets do not shear easily or evenly. Scaling of ductile iron is minimal in the forging range of 1,700° to 1,950° F and much less than that of plain-carbon steel. Ductile iron deforms in upsetting less readily than steel. Decreasing the silicon content from 4 to 2 pct is equivalent in plasticity to that gained by raising the upsetting temperature by 100° F. Flash, which is brittle in trimming, plays a prominent role in the forgeability of ductile iron, retarding further deformation after a certain degree of flash formation. More developmental work is needed regarding flash formation and control; vertical flashing could be a possible modification not evaluated in this work. The pattern of cracking is similar for forging temperatures over the range evaluated.

The following limitations to shape-forging of ductile iron were indicated in the evaluation:

1. For a given forging temperature and reduction, more time and energy are required for ductile iron than for steel.
2. It is possible to forge ductile iron geometries that do not require extreme deformations, abrupt section changes, and extensive piercing configurations.
3. Ductile iron is subject to cracking in the absence of overall die constraint.

The feasibility evaluation confirmed that parts can be forged from ductile iron, although modifications must be made to accommodate the characteristics of hot deformation. Selection of parts for forging must be consistent with these considerations and the properties needed in the part. The feasibility evaluation also confirmed the Bureau laboratory research that indicated that forged ductile iron has less ductility than forged steel, and that the directional nodule deformation in worked ductile iron results in anisotropy in properties. It was recognized that, for certain applications, these deficiencies could be offset by the superior properties of ductile iron, such as those of damping capacity, hardness, machinability, and scaling resistance. It was concluded that hot-worked ductile iron will not generally replace wrought steel; however, for certain parts, energy consumption can be less overall by finish-forging of readily castable rough shapes of ductile iron.

From this viewpoint, the limited tests with cast preforms were very encouraging. Such precast shapes apparently can eliminate or minimize problems encountered in forging from billets, and indications are that a reduction in overall energy expenditure could be realized as compared with conventional steel practice involving extensive billet deformation enroute to the production of forging stock.

Since it is likely that energy costs will continue to escalate, an integrated process involving melting, permanent mold casting, and direct feed (without cooling to ambient) into a forging machine might prove to be technically and economically feasible. It was intended that the results of these feasibility trials would stimulate further industrial interest in and development of hot-worked ductile iron as an additional structural material.

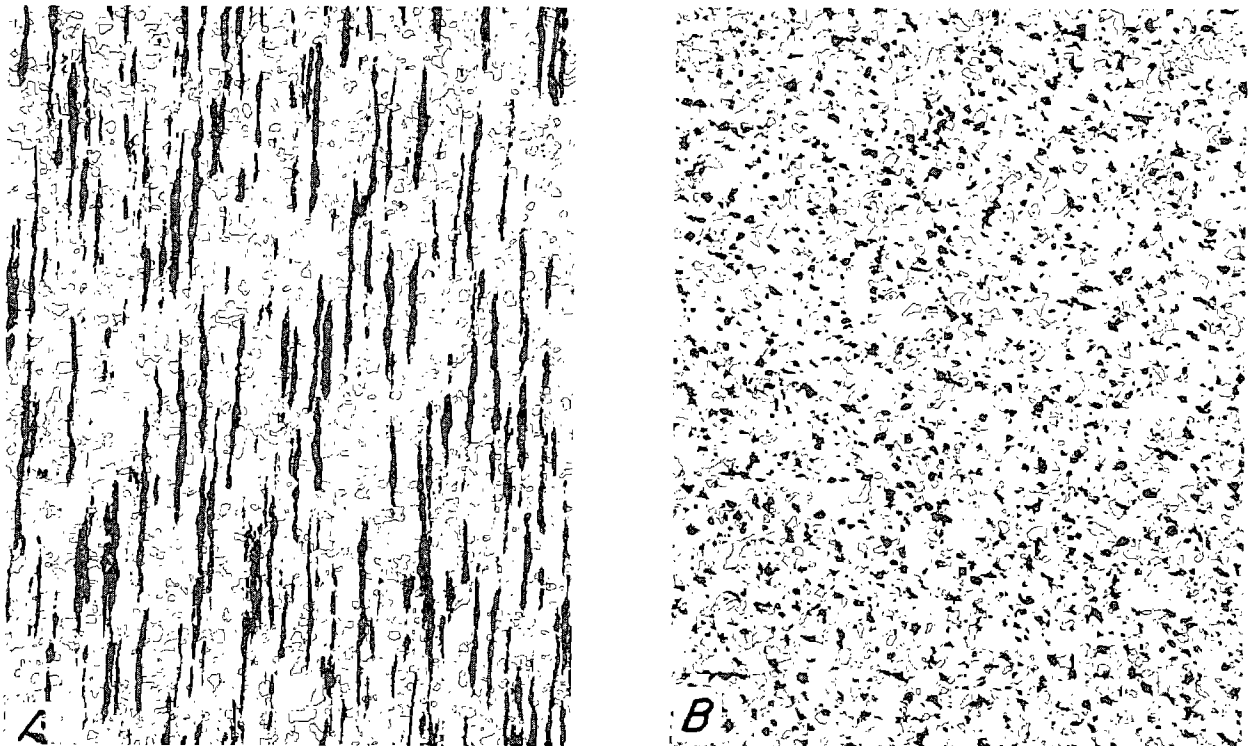


FIGURE 14. - Microstructures of 1/2-inch-diameter rod rolled to 94-pct reduction at 1,925° F. *A*, Longitudinal; *B*, transverse. Ferritize-annealed, X 100.

One other supplemental evaluation involved trials in rod rolling of ductile cast iron from continuous-cast ductile iron bar in the laboratories of the Department of Metallurgical and Materials Engineering at the University of Pittsburgh (28). Bar stock of ASTM 65-45-12 ductile iron, 2 inches in diameter, was rolled successfully through sequential square and oval mill configurations to 1/2-inch-diameter rod, representing approximately 94-pct reduction in cross section. Rolling temperature was either 1,750° or 1,925° F nominally, and roll speed was nominally 200 ft/min on the 15-hp reversing mill. The relative absence of cracking indicated that some additional deformation could have been possible. Figure 14 shows the microstructures of longitudinal and transverse sections of 1/2-inch-diameter rod, rolled at 1,925° F and ferritize-annealed.

DISCUSSION AND SUMMARY

From the standpoint of workability, there is considerable latitude for charge materials including various pig irons, although attention must be given to general compositional requirements for good nodularity. For the ranges investigated, workability was not noticeably affected by the C, Si, Mn, or the CE; however, it was affected by such factors as nickel content (soluble in austenite), unusually low nodule count, and obviously poorly formed nodules, although some vermicular graphite was tolerable. Variations in elements such as nickel and silicon deserve further attention.

Although ductile iron is less workable than steel, it has substantial workability between 1,550° and 1,950° F, which is lower than the range where steel working is normally started. Under appropriate conditions, it can be rolled to 90-pct reduction or more and upset forged to beyond 70-pct without serious cracking. Rolling reduction rate can affect workability, especially at large total deformation. As noted by Perry (22), the upper working limit is set by approach of incipient melting [Fe-C eutectic is at 2,107° F (1,153° C)], and the lower limit is influenced by the lower critical temperature where austenite becomes unstable and plasticity diminishes. The lower critical temperature increases with increased silicon content. Workability is better at 1,750° and 1,950° F than at 1,550° F; oxide scaling is greatest at 1,950° F. Cracks can propagate from surface defects, especially at lower working temperatures, where edges of thin materials may also crack more readily because of faster cooling.

The PMC materials, which, owing to faster solidification, have smaller and more numerous nodules than the SC materials and primary cementite, could be rolled about as readily as SC materials between 1,750° and 1,950° F. At 1,550° F, the increased cracking of the PMC materials is apparently related to the lesser fracture path between the more numerous nodules. The cementite could be decomposed during heating near 1,750° F before working. Somewhat slower solidification such as from preheating or insulating the molds would help decompose the cementite. Some cementite should be tolerable during working at the higher temperatures.

For a reason not yet explained, two SC slabs cracked severely during rolling at 1,950° F where workability was normally very good. The PMC ingots from these and the other heats were rolled at 1,950° F to 90-pct reduction with virtually no cracking.

Variation in composition affects mechanical properties more than it does workability, by altering pearlite-to-ferrite ratios (such as Mn and Si) and ferrite strength (Ni and Si). Because ductile iron is complex, composition and structure can markedly influence properties even in castings. Properties of sheet from PMC slabs differ from those of sheet from SC slabs because of the different nodule formation.

Heavily rolled material is characterized by high strength and anisotropy and low ductility, particularly for T specimens, which consistently have poorer properties. Ferritize-annealing reduces hardness and strength and improves ductility substantially, but anisotropy from the directional nodule deformation persists. Impact resistance of L specimens is about double that of T specimens, and annealed material about double that of material as-rolled to 70-pct reduction. Annealed L specimens exhibit ductile impact behavior at room temperature. Phosphorus up to 0.10 pct from the basic pig iron charges did not cause any substantial decrease in impact strength. Cross-rolling for part of the rolling reduction can reduce anisotropy in structure and properties. Because the interface is weaker, properties and perhaps workability may be affected somewhat by graphite deposition on existing nodules, which results

from pearlite decomposition, or lower working temperatures where austenite carbon solubility decreases. The low ductility of worked material would often dictate annealing, ideally before cooling after working.

Yield strengths are more consistent with those of hot-rolled low-carbon steel (3, p. 188), but L elongations are more consistent with those for high-carbon steel. Some of the better tensile values, such as for sheet rolled to 70-pct reduction at 1,750° F and annealed, and L yield and elongation values comparable to those of hot-rolled AISI 1030 steel, but the T elongations were much lower. Impact strength of ductile iron castings is only about one-third that of steel (3, p. 390). The poorer ductility and impact resistance of worked ductile iron would restrict its use to applications where these deficiencies would be tolerable. However, its good castability, machinability, damping capacity, and wear and corrosion resistance, because of the high carbon and silicon, could be offsetting factors.

Damping capacity is enhanced in worked ductile iron. The L sheet specimens exhibited somewhat greater improvement than T specimens, >60 and >40 pct, respectively, relative to the cast material. Ferritize-annealed ductile iron sheet had more than twice the damping capacity of the cast material.

The trial die-forging tests reported previously demonstrated that die forging of ductile iron is feasible if certain factors are recognized, such as the influence of silicon content, the need for die constraint, and the importance of designing for control of flash, maximum directional reduction, and piercing deformation. Bar rolling can be readily carried out to at least 90-pct reduction in cross-sectional area.

Hot-working of ductile iron deserves attention in light of advances in technology. With care, large ductile iron castings with good nodularity can be made (12). Rare earths can alleviate adverse nodularity effects of impurities such as titanium and lead (32). Technology is available for minimizing magnesium fading during extended holding of melts, permitting many castings from single heats (14). Ductile iron is being nodulized with unalloyed magnesium in converter ladles (1). Mag-Coke, developed for ductile iron nodulization, now serves to desulfurize pig iron in torpedo cars between blast furnace and steelmaking furnace (16); additional amounts could feasibly nodulize iron castings for hot-working. There is increasing interest in casting ductile iron in permanent molds (34), nodulizing in the mold (15), and coining of castings (23).

Several areas may offer potential for hot-working of ductile iron. For example, it may be possible to treat hot metal directly from the blast furnace to desulfurize, nodulize, and balance chemistry, and cast into ingots for hot-working into shapes. Permanent mold castings can develop adequate structures and may offer some economical benefits. More advantage could be taken of ductile iron's forgeability for certain items, perhaps as forging of cast preforms. Although ductile iron is sensitive to rolling-deformation rate at heavy reductions, high-energy-rate forming deserves attention because of the reported success with forging gray cast iron (2). Items might be cast to rough shape and finished with some rolling or forging, perhaps in conjunction with continuous-casting. Innovative thinking should suggest other areas.

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¹⁰Titles enclosed in parentheses are translations from the language in which the item was published.

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APPENDIX A.--HARDNESS

Hardness data for sheet as-rolled to 90-pct reduction at various temperatures and ferritize-annealed are listed in tables A-1 and A-2 for sand-cast and permanent mold materials, respectively.

Table A-3 gives hardness values for sand-cast materials as-rolled to 70-pct-reduction at 1,750° F and ferritize-annealed.

TABLE A-1. - Hardness of sand-cast materials rolled to 90-pct reduction¹ and ferritize-annealed

Heat No.	Rolling temperature, ° F	Hardness, Rockwell A	
		As-rolled	Ferritize-annealed
63-A.....	1,750	56	28
67-A.....	1,750	61	35
68-A.....	1,750	63	36
64-B.....	1,550	50	30
	1,750	56	30
	1,950	66	38
66-B.....	1,550	55	35
	1,750	58	37
	1,950	69	42
70-B.....	1,550	56	37
	1,750	62	37
	1,950	67	43
65-C.....	1,550	55	32
	1,750	57	32
	1,950	69	41
81-D.....	1,550	56	35
	1,750	61	38
	1,950	68	46
82-D.....	1,750	56	34
97-E.....	1,750	60	32
98-E.....	1,750	61	34
A01-F.....	1,750	59	38
A02-F.....	1,550	57	31
	1,750	62	39
	1,950	71	48

¹At 90-pct reduction, 0.10 inch thick.

TABLE A-2. - Hardness of permanent mold materials rolled to 90-pct reduction¹ and ferritize-annealed

Heat No.	Rolling temperature, ° F	Hardness, Rockwell A	
		As-rolled	Ferritize-annealed
54-B.....	1,550	43	41
	1,750	49	40
	1,950	63	42
58-B.....	1,550	51	44
	1,750	52	44
	1,950	65	45
62-C.....	1,550	52	38
	1,750	54	41
	1,950	67	45
81-D.....	1,750	62	43
97-E.....	1,750	58	40
98-E.....	1,750	59	45
A01-F.....	1,750	60	45
A02-F.....	1,550	56	39
	1,750	61	44
	1,950	67	50

¹At 90-pct reduction, 0.18 inch thick.

TABLE A-3. - Hardness of sand-cast materials rolled to 70-pct reduction¹ at 1,750° F and ferritize-annealed

Heat No.	Hardness, Rockwell A	
	As-rolled	Ferritize-annealed
64-B.....	64	41
66-B.....	61	42

¹At 70-pct reduction, 0.30 inch thick.

TABLE A-4. - Hardness of billets¹ forged to 85-pct reduction and ferritize-annealed

Heat No.	Forging temperature, ° F	Hardness, Rockwell A	
		As-forged	Ferritize-annealed
66-B.....	1,750	54	34
	1,950	62	43

¹Permanent mold castings.

APPENDIX B.--TENSILE PROPERTIES

Tables B-1 and B-2 list additional tensile properties of sand-cast and permanent mold materials, respectively, that were not listed in table 6 of the text. The data are for sheet as-rolled to 90-pct reduction of various temperatures and ferritize-annealed.

Tensile data for sand-cast materials as-rolled to 70-pct reduction at 1,750° F and ferritize-annealed are given in table B-3.

For the sheet rolled from sand castings, the average standard deviations (four specimens for each condition) for tensile strength, yield strength, and elongation, respectively, were L (as-rolled) = 4,832 psi, 2,001 psi, and 0.57 pct; T (as-rolled) = 4,437 psi, 2,621 psi, and 0.29 pct; L (annealed) = 1,041 psi, 532 psi, and 1.02 pct; and T (annealed) = 1,379 psi, 503 psi, and 0.60 pct.

For the sheet rolled from permanent mold ingots, the corresponding values were L (as-rolled) = 2,834 psi, 1,310 psi, and 0.52 pct; T (as-rolled) = 2,663 psi, 1,803 psi, and 0.40 pct; L (annealed) = 862 psi, 642 psi, and 1.38 pct; and T (annealed) = 1,113 psi, 433 psi, and 0.50 pct.

TABLE B-1. - Tensile properties of sand-cast materials rolled to 90-pct reduction¹ and ferritize-annealed

Heat No.	Rolling temp, °F	Orientation	As-rolled			Ferritize-annealed		
			Tensile strength, psi	Yield strength, psi	Elongation, pct	Tensile strength, psi	Yield strength, psi	Elongation, pct
63-A..	1,750	L	116,600	91,700	3	51,200	35,600	10
		T	60,300	59,700	1	38,900	34,200	3
67-A..	1,750	L	134,200	105,200	2-1/2	56,200	40,700	9
		T	58,000	58,000	1-1/2	37,300	36,600	1-1/2
68-A..	1,750	L	127,700	97,200	2-1/2	57,700	43,000	8-1/2
		T	74,100	74,100	1	40,700	39,400	1-1/2
64-B..	1,550	L	86,200	75,800	3	47,900	36,000	7
		T	54,300	53,900	1	36,400	32,100	2-1/2
	1,750	L	109,100	84,600	3	50,000	35,300	10
70-B..		T	72,000	65,900	2	39,000	32,000	3
	1,950	L	150,200	97,600	5	58,400	37,900	16
		T	112,200	91,600	1-1/2	49,200	36,800	4
70-B..	1,550	L	91,800	75,700	3	57,500	45,200	7
		T	62,800	62,000	1	45,700	41,400	2
	1,750	L	135,900	98,700	3-1/2	60,700	44,300	13
65-C..		T	94,600	85,000	1-1/2	48,200	41,700	2-1/2
	1,950	L	149,100	109,100	1-1/2	64,300	46,100	17
		T	112,200	90,200	1-1/2	54,600	43,900	4-1/2
65-C..	1,550	L	86,700	77,800	3	45,900	37,700	5
		T	52,300	58,000	1-1/2	33,100	32,500	1-1/2
	1,750	L	111,700	93,500	2	51,900	38,700	9
82-D..		T	72,000	70,000	1	39,300	35,500	2-1/2
	1,950	L	158,900	109,600	4	62,400	42,900	14
		T	117,400	106,000	2	48,000	38,600	4
82-D..	1,750	L	114,100	92,900	1-1/2	52,900	39,900	8
		T	64,700	64,700	1/2	36,800	34,700	1-1/2
97-E..	1,750	L	133,000	95,200	3	54,600	38,200	12
		T	91,800	82,800	1-1/2	42,100	34,800	4
98-E..	1,750	L	132,300	102,100	2-1/2	59,300	43,400	11
		T	91,400	83,200	1-1/2	45,500	39,400	3-1/2
A01-F.	1,750	L	137,100	114,200	1-1/2	62,300	46,500	11
		T	85,700	80,700	1-1/2	48,600	42,700	3
A02-F.	1,550	L	106,000	82,500	3	54,000	42,000	9
		T	68,500	67,800	1	40,900	37,000	2
	1,750	L	141,000	96,900	3-1/2	59,600	42,300	14
A02-F.		T	98,700	87,800	1-1/2	47,000	38,600	3-1/2
	1,950	L	165,500	119,200	4-1/2	68,800	48,100	17
		T	136,700	117,700	1-1/2	57,100	43,600	5

¹At 90-pct reduction, 0.10 inch thick.

TABLE B-2. - Tensile properties of permanent mold materials rolled to 90-pct reduction¹ and ferritize-annealed

Heat No.	Rolling temp., ° F	Orientation	As-rolled			Ferritize-annealed		
			Tensile strength, psi	Yield strength, psi	Elongation, pct	Tensile strength, psi	Yield strength, psi	Elongation, pct
54-B..	1,550	L	73,500	55,200	3	56,100	41,200	5-1/2
		T	51,500	49,100	2	45,600	38,400	2
	1,750	L	89,900	61,600	5-1/2	61,600	40,200	10-1/2
		T	60,900	52,100	2	49,500	39,100	3
	1,950	L	115,100	73,300	4	61,200	44,000	12-1/2
		T	91,300	64,300	2-1/2	51,900	40,700	4
62-C..	1,550	L	90,500	69,900	2-1/2	53,100	42,600	5
		T	59,400	56,200	1	40,600	39,200	1-1/2
	1,750	L	110,300	73,000	4	59,900	43,700	9-1/2
		T	75,500	61,300	1-1/2	49,100	41,200	3
	1,950	L	156,500	104,200	4-1/2	65,300	48,800	14
		T	115,700	93,300	1-1/2	55,700	44,700	4-1/2
97-E..	1,750	L	121,900	82,400	3-1/2	59,600	40,600	13-1/2
		T	85,800	64,600	2	49,300	37,900	4-1/2
98-E..	1,750	L	127,300	84,500	4	63,500	45,000	13
		T	86,400	68,900	2	52,700	42,400	3-1/2
A01-F.	1,750	L	122,100	86,600	3	65,800	47,500	13-1/2
		T	86,800	70,500	2	56,900	44,900	4-1/2
A02-F.	1,550	L	120,800	75,400	4-1/2	59,900	44,300	11-1/2
		T	76,300	69,600	1-1/2	46,900	41,600	3
	1,750	L	134,900	86,000	4-1/2	63,600	45,000	16-1/2
		T	94,500	72,400	2	56,800	41,300	6-1/2
	1,950	L	152,400	97,700	5	70,300	50,900	19
		T	128,400	91,200	2-1/2	64,800	46,700	9-1/2

¹At 90-pct reduction, 0.18 inch thick.

TABLE B-3. - Tensile properties of sand-cast materials rolled to 70-pct reduction¹ at 1,750° F and ferritize-annealed

Heat No.	Orientation	As-rolled			Ferritize-annealed		
		Tensile strength, psi	Yield strength, psi	Elongation, pct	Tensile strength, psi	Yield strength, psi	Elongation, pct
64-B....	L	126,300	76,900	5	56,800	35,500	19
	T	86,600	69,800	2	46,300	33,400	5
66-B....	L	133,400	81,000	5-1/2	60,200	37,200	20-1/2
	T	103,900	70,000	3	52,200	36,400	7

¹At 70-pct reduction, 0.30 inch thick.

TABLE B-4. - Tensile properties of billets¹ forged to 85-pct reduction and ferritize-annealed

Heat No.	Forging temp., ° F	As-forged			Ferritize-annealed		
		Tensile strength, psi	Yield strength, psi	Elongation, pct	Tensile strength, psi	Yield strength, psi	Elongation, pct
66-B..	1,750	64,800	64,100	1-1/2	50,200	39,200	4
	1,950	97,800	77,700	2	56,400	41,600	5

¹Permanent mold castings.

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<p>The Bureau of Mines investigated hot-rolling and forging characteristics of experimental ductile iron castings, both sand and permanent-mold, made with charges containing up to 70 pct foundry pig iron and 95 pct steelmaking pig iron. Between 1,550° and 1,950° F, most castings could be rolled to 90-pct reduction or forged to 70-pct reduction without serious cracking. Charge and composition have less bearing on workability than on subsequent properties. Permanent mold castings could be worked as readily as sand castings at 1,750° and 1,950° F. Plasticity improved with temperature. Small billets were also forged cold to 50-pct reduction without cracking. With equivalent nodularity, composition affects properties of wrought materials by altering matrix structure and strength. Properties vary with reduction and improve with increasing working temperature. Rolled material has high strength and anisotropy, and low ductility, particularly in the transverse direction. Annealing reduces strength and improves ductility, but anisotropy persists. At 70-pct reduction, impact resistance in the longitudinal direction is about twice that in the transverse. Annealing roughly doubles impact resistance. Deformation enhances damping capacity. The feasibility of die-forging and bar-rolling of ductile iron was evaluated in trial tests conducted under a Bureau contract. Although workability and ductility of ductile iron are inferior to those of steel, more advantage could be taken of ductile iron's plasticity to work rough shapes to final dimensions.</p>					
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