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Some Factors Affecting the Hot Workability of Ductile Iron

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ABSTRACT

The hot workability of ductile iron has been studied in the range of 2.08 to 4.36% C, using 10-lb ingots. The highest workability was observed at low carbon levels. In a preliminary experiment, ductile iron with 3.24% C was rolled to 3/64-inch strip at 1850F (1010C). Other ingots with about 2.25% C developed no cracks when rolled without reheats from 1900–1500F (1035–815C). Workability decreased with increasing carbon content. Silicon variations had little effect. Workability was considerable better at 1950F (1065) than at 1850F (1010C). Workability correlated well with hot tensile properties at rolling temperatures. Forging experiments showed promise.

Keywords: ductile iron, hot workability, carbon effects, silicon effects, temperature effect, rolling schedule effect, forging

INTRODUCTION

Ductile iron is one of the greatest metallurgical discoveries of the 20th century, being the first cast iron with useful ductility and toughness in the as-cast condition. Understandably, its inherent ductility has prompted some researchers to investigate its workability at temperatures in the austenitic range. Perry and Rehder hot rolled and forged experimental ingots with reasonable success.[1] They observed that cracking became more severe as rolling temperatures were lowered from 1065–845C (1950–1550F). Unskov and Berezhkovskii were able to forge ductile iron bars quite extensively but had less success with rolling.[2] They considered 1050–800C (1920–1470F) to be the optimum range for forging. The extrusion of bars and tubes at 980C (1800F) using glass lubricants was described by Blake and Arnold as erratic, but some sound products were attained.[3] Neumeier et al. evaluated the workability and properties of ductile iron ingots cast in permanent and sand molds, finding good workability at higher temperatures.[4]

To gain a better understanding of factors affecting the behavior of ductile iron during hot working, this study evaluated the influence of chemical composition, severity of rolling, and rolling temperature on the hot workability of experimental ingots cast in permanent molds. We also investigated whether hot tensile tests might provide useful guidance on hot workability.

EXPERIMENTAL METHODS

The ingots used in this study were 2.25 in. square by 10 in. in length, weighing about 10 lb each. They were produced in cast-iron molds from induction melted 100-lb heats of ductile iron. Compositions were 2.08–4.36% C, 0.63–2.13% Si, <0.1–0.49% Mn, ~0.02% P, ~0.02% S, and <0.01–0.047% Mg; all values are listed in Table 1. Carbon contents lying well beyond those in commercial ductile iron were intended to ‘prove the point’ about carbon’s effect. The ingots were graphitized at 1700F (927C) for 2 hours to facilitate riser removal. Nodularity ranged from about 90 percent at the lowest carbon levels to about 70–80 percent for all but Ingots R-9 & R-10. These had been dead melted from Sorelmetal, yielding carbon and carbon equivalent values far above normal, with some resulting exploded graphite. Also, the low residual titanium content led to the presence of some vermicular graphite. Ni-Mg was used to treat three heats, for the sake of achieving low silicon content within the group to create a silicon series.

Table 1. Chemical Analysis of Experimental Ingots, Pct.

Ingot No.	C	Si	Mn	P	S	Mg
R-1	2.08	1.44	0.49	NA	0.028	NA
R-2	3.24	2.13	0.37	NA	0.023	0.027
R-6	2.25	1.73	0.21	0.014	0.018	0.028
R-7	3.08	1.79	0.29	0.013	0.019	0.047
R-8	3.85	1.78	0.29	0.014	0.018	0.044
R-9	4.16	1.93	0.22	0.017	0.017	0.045
R-10	4.36	1.76	0.18	0.022	0.017	0.035
R-11*	3.87	0.63	<0.1	0.022	0.017	0.035
R-12*	3.87	1.00	<0.1	0.019	0/018	0.015
R-13*	3.79	1.45	<0.1	0.025	0.017	<0.010
R-14	2.22	1.63	0.30	0.013	0.017	0.023
G-3	3.50	1.95	0.31	0.014	0.014	NA
*1.25%Ni						

The two-high rolling mill had rolls 9.5 inches in diameter, with graduated, alternating diamond and square grooves, plus a central plate/strip zone. At each roll-setting, the work was rotated 90 degrees about its long axis and given a second pass because of 'earing,' to help maintain a nearly square cross-section. The mill was operated at a rolling speed of 1.25 in./sec. Ingots were heated in a gas-fired furnace for 1.5 hrs. before rolling. All ingots, except R-6 and R-14, were rolled at fixed temperatures: 1850 and 1950F (1010 and 1065C) with 5 min. reheats between each reduction. At each temperature, lighter (3–5%) and heavier (10–15%) reductions were employed. Ingots R-6 and R-14 were hot rolled from 1900 to 1500F (1035 to 815C) under the heavier reductions, without reheating.

Three ingots were hot-tensile tested by preparing tensile specimens from the ingots and testing them at 1850, 1900, and 1950F (1010, 1038, 1065C) in an air atmosphere. Selected metallography and photography were performed.

RESULTS AND DISCUSSION

Experimental results will be discussed in the following order:

1. Preliminary studies;
2. Effects of composition and rolling conditions on hot workability; and
3. Correlation of workability with hot tensile test data.

PRELIMINARY STUDIES OF ROLLING, FORGING, AND MICROSTRUCTURES

Two heats were prepared initially, to explore hot-working behavior at low and moderate carbon concentrations. Ingots from both heats R-1 (2.08% C / 1.44% Si), and R-2 (3.24% C / 2.13% Si) were reduced 10-15% per reduction at 1850F (1010C), with 10-minute reheats between reductions, to bars ½ inch square, and strips 3/64 and 1/4 inch thick, respectively. The bar and strip exhibited negligible cracking. A short piece of the 3/64 inch strip is shown in Figure 1.

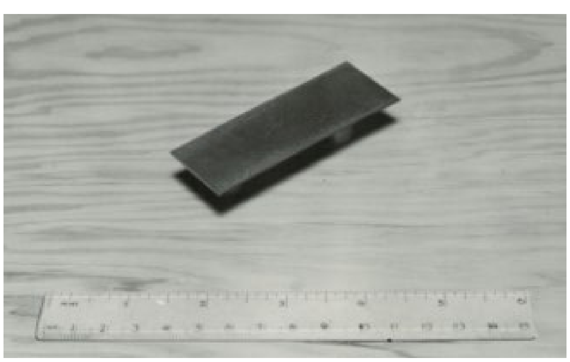


Figure 1. Ingot R-1 was rolled under heavier reduction at 1850 F (1010 C) to 3/64-inch-thick strip.

Tensile properties of the strips, air-cooled from the rolling temperature, are shown below:

	Y.S	T.S.	Elongation
R-1	127 ksi	183 ksi	3 pct
	876 MPa	1262 MPa	
R-2	100 ksi	161 ksi	5 pct
	689 MPa	1110 MPa	

It can be seen that the low-carbon R-1 strip achieved rather remarkable strength properties in the as-rolled condition. The effect of hot rolling on graphite spheroid shape is evident in Figure 2, for air-cooled R-2 strip of ¼ inch thickness, reduced 95% in cross-section. Spheroids are greatly elongated in the rolling direction. The irregular shape presumably is due to repeated and complex deformation and recrystallization of the austenite during hot rolling. Most particles are nearly uniform in thickness, but a few distorted spheroids, presumably remnants from the larger ones, are evident.

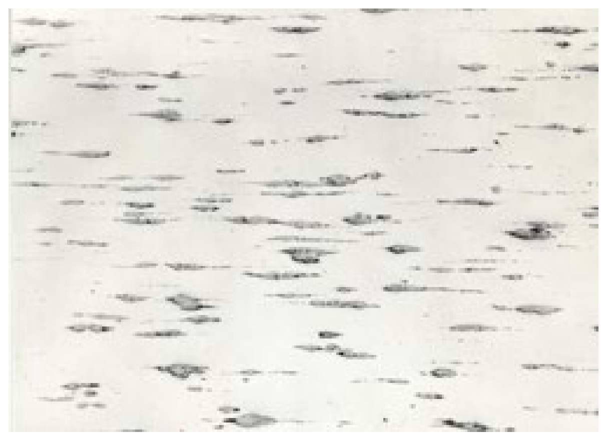
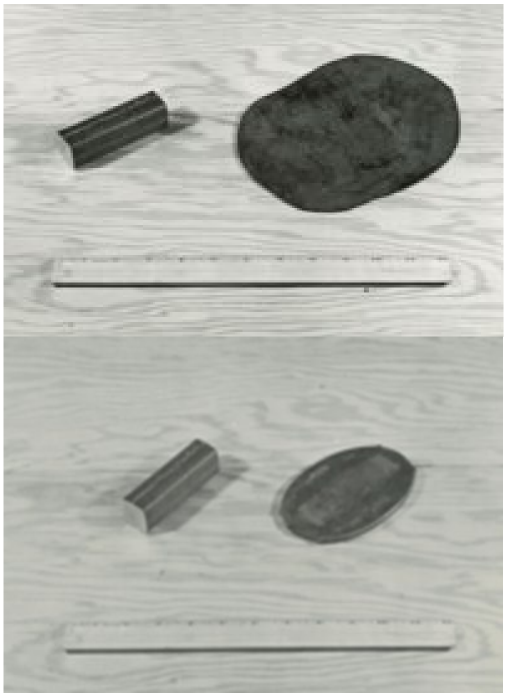


Figure 2. Microstructure of Ingot R-2, rolled to ¼-inch strip at 1850F (1010C).

To examine forging effects, hot-rolled bars of preliminary heats R-1 and R-2 were flattened at 1850F (1010C), with a 3500-lb steam hammer, Fig. 3. The lower-carbon bar R-1 was flattened from a 7/8 inch-thick bar to 5/64 inch-thick plate in three blows without cracking (Fig. 3a). The higher-carbon bar R-2 was flattened from 7/8 inch-thick bar to 5/16 inch thick plate, rupturing at one end on the second blow (Fig. 3b). Obviously, the increased amount of graphite impaired workability.



Figures 3a & 3b. Bars R-1, forged to 5/64 inch plate, and R-2 forged to 5/16 inch plate, respectively.

EFFECTS OF CHEMICAL COMPOSITION AND ROLLING CONDITIONS ON HOT WORKABILITY

The lower workability of Heat R-2 relative to Heat R-1 in the previous section suggested that the effect of carbon concentration required careful study. We also decided to evaluate the effects of silicon concentration, rolling temperature, and severity of rolling reductions on behavior of ductile iron ingots, under controlled conditions.

Carbon

Results for five ingots having carbon contents of 2.22 to 4.36%, all with about 1.8 % silicon, are listed in Table 2. Using the number of cracks per hot-rolled 1-inch-square bar as an index of workability, the performance of ingots during hot rolling at 1850F (1010C) is seen to be seriously impaired by increasing carbon content, for both the heavier and lighter rolling schedules. This difference is shown graphically in Figure 4, and visually in the photographs of Figure 5, where the high-carbon bars R-9 and R-10 are both highly cracked under the heavier rolling schedule; but less severely under the lighter schedule.

The good workability of ductile iron at lower carbon levels was confirmed by the behavior of the Group 2 ingots in Table 2. Ingots of 2.22 and 2.25% C were rolled without reheating, starting at 1900F and ending at 1500F (1038-816C), and developed no cracks. The harmful effect of carbon on workability is apparently due to the larger quantities of graphite present at higher carbon concentrations. Greater numbers of graphite particles provide more locations for crack initiation during hot working. Cracks, once initiated, would then propagate more readily in higher carbon iron, because of the shorter mean free path between particles.

The morphology of the graphite is believed to have contributed to the negative effect of carbon on workability. The graphite spheroids in the present heats become less perfect as the carbon content increases; especially in hypereutectic R-9 and R-10, which, as noted previously, possess some clusters of exploded graphite. Because these carbon contents are well above the normal 3.2-3.6% range for ductile iron, this should be considered. It seemed important to evaluate extreme carbon levels, to help 'prove the point' about its effect.

Table 2. Effects of Carbon Content & Rolling Schedule on Workability

Ingot No.	Pct. C	Pct. Si	Quantity of Cracks per 1-inch Square Bar	
			Heavier Reductions 10 - 15 Pct.	Lighter Reductions 3 - 5 Pct.
Group 1: Rolled at 1850 F (1010 C), 5-minute Reheats				
R-6	2.25	1.73	1	0
R-7	3.08	1.79	6	0
R-8	3.85	1.78	51	5
R-9	4.16	1.93	156	77
R-10	4.36	1.76	151	93
Group 2: Rolled without Reheats, 1900 to 1500 F (1035 to 815 C)				
R-6	2.25	1.73	0	---
R-14	2.22	1.63	0	---

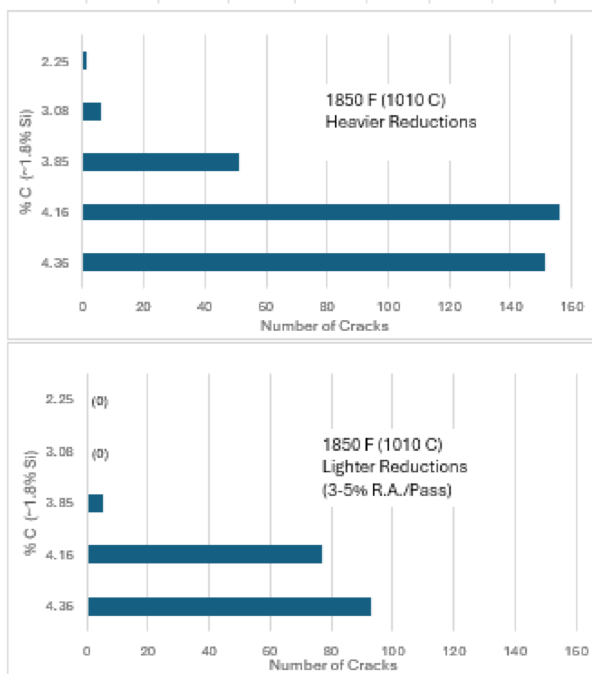


Figure 4. Effect of C content & reductions on workability.

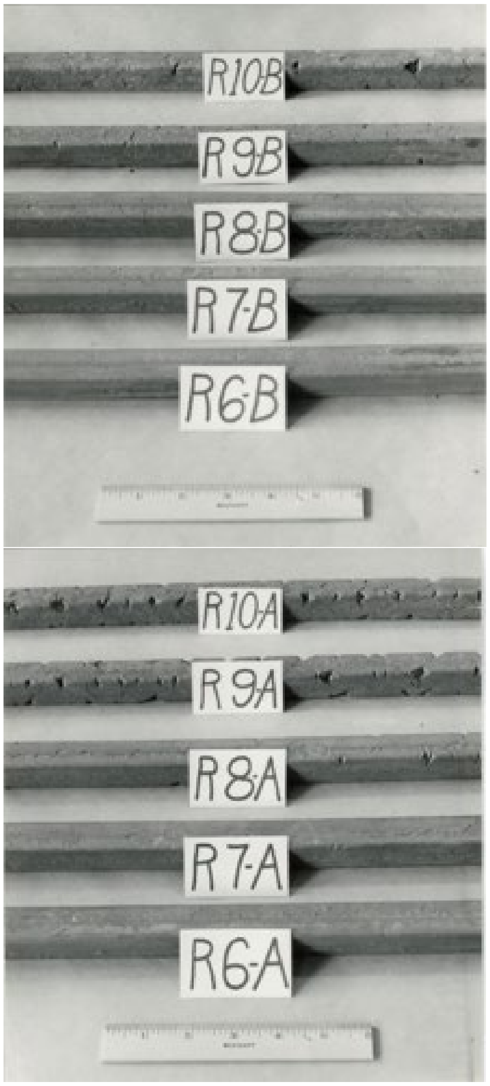


Figure 5. One inch bars of the carbon series rolled at 1850 F (1010 C) under heavier reductions (bottom) and lighter reductions (top).

Silicon

Results for three ingots having silicon contents of 0.63-1.45%, all with about 3.85% carbon, are listed in Table 3. Cracking at 1850 F (1010 C) was minimal, just 8-9 cracks per bar. At 1950 F (1065 C) there was only one crack, indicating the better workability at this temperature. One contributing factor to this is the somewhat smaller volume fraction of graphite nodules, owing to the higher carbon solubility in austenite at the higher temperature.

Considering the likely effect of volume fraction on workability, it is easy to understand the much greater cracking in Ingot R-9 at both temperatures, because of its ~0.3% higher carbon content than in the silicon series. As seen, R-9 has markedly fewer cracks at the higher temperature. The low, and uniform, cracking of the silicon series is evident in the bar graph in Figure 6.

Table 3. Effect of Silicon Content & Temperature on Workability

Ingot No.	Pct. C	Pct. Si	Quantity of Cracks per 1-inch Square Bar, 10-15 Pct R.A./pass, 5 Min. Reheats	
			Rolled at 1850 F (1010 C)	Rolled at 1950 F (1065 C)
R-9	4.16	1.93	156	90
Silicon Series				
R-11	3.87	0.63	8	1
R-12	3.87	1.00	9	0
R-13	3.79	1.45	9	0

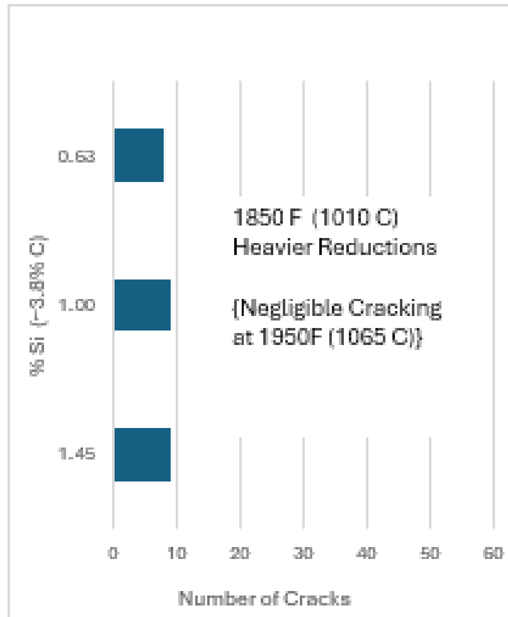


Figure 6. Silicon variations show negligible effect on cracking.

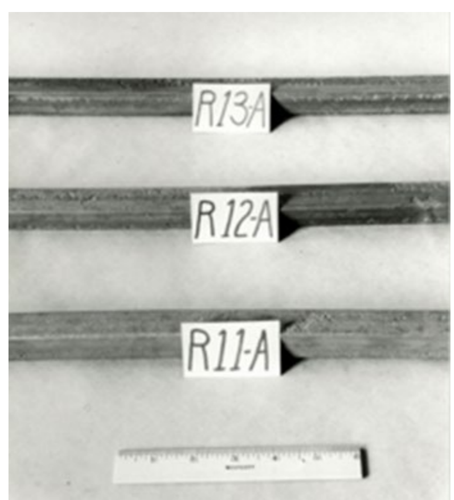


Figure 7. Three bars of the silicon series, rolled under heavier schedule at 1850F (1010C).

CORRELATION WITH HOT TENSILE TEST PROPERTIES

A series of hot tensile tests were performed to determine if the ductility of ductile iron measured in tensile tests at rolling temperatures can serve as an index of hot workability. Tests were performed on specimens from an ingot having very poor workability (R-10), and two with very good workability (R-14 and G-3). Specimens were machined from graphitized but unrolled ingots and were held 1.5 hr at the testing temperature to simulate the soaking time for ingots. Tests were performed at 1850, 1900, and 1950 F (1010, 1035, and 1065 C). Specimens were strained at 3.5 pct per second to simulate, to some extent, the high strain rate during rolling. The data in Table 4 shows a definite correlation. Ingot R-10, which developed 151 cracks when rolled at 1850 F (1010 C) under the heavier schedule had elongation and reduction of area values of just 18 & 20 pct, respectively at the same temperature. These values are far below those for Ingot R-14 at its initial rolling temperature of 1900 F (1035 C), and Ingot G-3, rolled at 1950 F (1065 C), both ingots that developed no cracks during rolling at those respective temperatures.

This favorable relationship of hot tensile ductility and hot workability suggests the use of such tests to predict the hot workability of ductile iron. For the rolling conditions of this study, ductility values of 50 pct or more at the rolling temperature would seem to ensure good workability and could be used as a screening test for workability of candidate chemistries, both experimental and production.

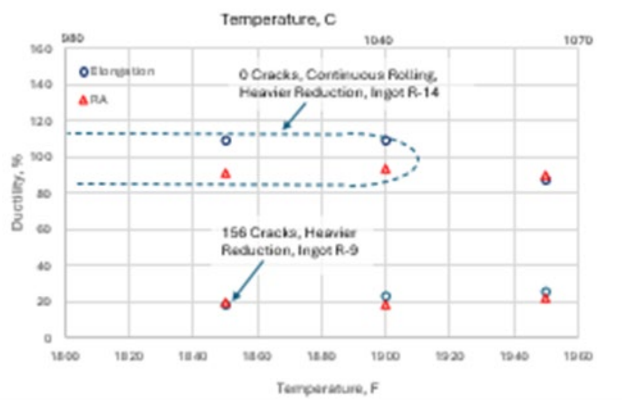


Figure 8. Correlation of hot tensile test ductility values with workability.

Table 4. Relation between Workability & Tensile Properties Measured at Rolling Temperatures

Temperature, F	T.S., psi	Elong., %	R.A., %	No. of Cracks per bar, @ 10 - 15%/pass
Ingot R-14 (2.22% C, 1.63% Si)				
1850 (1010 C)	7300	109	91	---
1900 (1035 C)	6530	109	94	0*
1950 (1065 C)	5800	88	90	---
Ingot G-3 (3.50% C, 1.95% Si)				
1850 (1010 C)	10,000	34	31	---
1900 (1035 C)	6225	333	28	---
1950 (1065 C)	5450	52	41	0
Ingot R-10 (4.36% C, 1.76% Si)				
1850 (1010 C)	6425	18	20	151
1900 (1035 C)	5700	23	19	---
1950 (1065 C)	5150	26	22	---

*Rolled without reheats, from 1900 to 1500 F (1035-815 C)

APPLICABILITY

The possibility of hot working, even heavily, ductile iron that is normally used in the as-cast shape, presents the possibility of a challenging, but hopefully rewarding, brainstorming session for cast iron foundrymen. One stimulus might be the thought of producing a ‘sideline’ product in times of slack demand. Reinforcing bar comes to mind, a product that could be hot rolled from continuously cast bars, and that would be attractive because of the superior corrosion resistance of ductile iron over steel. The slightly lower weight of ductile iron adds to its attraction for ‘rebar.’ Surely there are some other candidates for ‘sideline’ products.

The corrosion resistance and machinability of ductile iron, and its ability to develop any matrix, ranging from ferrite to martensite, make it attractive also as a mill product for special applications. Moreover, the very good castability of ductile iron suggests the possibility of simplifying the forging phase of production by casting to an advanced shape and then using forging only to provide the final features or even coining to the exact final dimensions. This study clearly shows that carbon is the ‘enemy’ of workability in ductile iron. If heavy deformation is desired, carbon levels at the low end of the 3.2-3.6 pct range that is common for ductile iron, or preferably well below this range, are most likely to bring successful results. With widespread use of electric melting in induction or arc furnaces, there is no serious obstacle to 1) achieving such lower carbon levels, and 2) providing the slightly higher pouring temperatures required at lower carbon contents. If lower hot deformations are considered, success can quite likely be found within the normal range of carbon contents for ductile iron.

CONCLUSIONS

Regarding the hot workability of ductile iron:

- Workability is favored by low carbon contents and high temperatures.
- Silicon has little, if any, effect.
- Lighter reductions result in less cracking.
- Ductility measured in tensile tests at rolling temperatures is a good indicator of workability.

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