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The Influence of Copper on Steel.

Report No. 342/6
Watertown Arsenal

OAK/N
February 7,1917.

The Influence of Copper on Steel.

The following information is collected from the most important articles on the subject of the Influence of Copper on Steel, and for the most part is based on researches conducted since 1900. A few references of earlier date, together with some brief conclusions will be given.

1. Louis Savot (1627) stated that copper made iron brittle and mentioned the difficulties experienced by "smiths" in working iron containing copper.

2. Jars (1774) said "it is generally thought that copper is a pest for iron", but adds that Cramer told him that copper up to 1% had no deleterious effect.

3. Faraday and Stoddard,(1820) melted steel with 2% Copper but found the steel was not improved.

4. Mushet (1835) found steel melted with 5% Copper to be considerably hardened, but could not be forged. He concluded, as a result of his experiments, that copper unites with iron more freely as the carbon percentage decreases.

5. Willis (1880) found that 0.1% Copper did not produce any appreciable effect on the quality of steel.

6. Wasum (1882) made experiments in which he investigated the effect of Copper alone, of Sulphur alone, and the two together upon steel. He concluded that, up to 0.862% Copper, this element did not produce a trace of red-shortness. Copper and Sulphur combined did not appear to produce red shortness unless the percentage of Sulphur alone was high enough to cause it.

7. Choubley (1884) confirms the observations of Wasum on the rolling qualities of copper steel, and found that even 1.0% of copper in the absence of Sulphur did not produce red-shortness.

8. Holtzer (1889) exhibited some copper steels at the Paris Exposition in 1889 containing from 3 to 4% of Copper. They were remarkable for their extremely high elastic limit, especially the hardened bars, which gave values as high as 142,228 lbs. per sq. inch.

9. Brustlein (1889) says that steels with more than 1% copper were decidedly red short and had no future; also that Copper did not make a thorough mixture with steel, and that it favored the formation of blowholes.

10. Ball and Wingham (1889) observed in the course of their experiments that the presence of carbon seemed to favor the more intimate mixture of copper with iron. Some of their specimens with small percentages of carbon and copper worked well both cold and hot. They found that copper made iron and steel extremely hard, and that "within certain limits copper does not prejudicially affect the mechanical properties of steel."

11. Riley (1890) claims to have observed that copper is not really alloyed with iron but exists disseminated throughout the metal. If aluminum is used in making the alloy, a perfect mixture is obtained.

12. Schneider (1890) obtained a patent upon a method of alloying copper with steel. His alloys were remarkable for great strength, tenacity, and malleability. They were claimed to be especially useful in the manufacture of ordnance armor plate, gun tubes, projectiles, etc. These alloys contained between 5 and 20% Copper.

13. Scranton (1891) of the Scranton Steel Works, is said to habitually manufacture Bessemer T rails with 0.5% to 0.55% Copper, which are not red short.

14. Howe(1891) declares that iron and copper unite in all proportions and the alloys of iron with small amounts of copper are said to be homogeneous. He also states that copper has a similar effect to sulphur in causing red shortness and incapability of being welded.

15. Garrison (1891) points to the very high elastic limit of copper steel.

16. Arnold (1894) had no difficulty in hammering an ingot with .1% carbon and 1.8% copper. He states that copper has a greater influence than manganese in raising the elastic limit.

17. Colby (1899) states that small percentages of copper have no deleterious effect upon steel. He made propellor shafts for United States battleships,and gun tubes,by forging steel containing copper,which fulfilled the specifications of the Government. The tensile strength was not less than 75,000 lbs. per sq. inch, and the elastic limit not less than 36,000 lbs. per sq. inch, with elongation of 20% in 2". It stood bending fairly well and could be successfully welded. The copper content was 0.565%.

18. Williams (1900) experimented upon the atmospheric corrosion of copper steel and concludes that the loss due to weathering decreases as the copper increases.

19. Lipin observed that copper increased the fluidity of steel and makes it more and more crystalline at the fracture. He found steel to be red short when the copper reached 4.7%. He thinks tool steel may contain copper up to 1%, and suggests quenching in oil instead of water. He concludes that the presence of copper need not cause apprehension, although there may not be any advantage in its presence. He also found that as the percentage of carbon increased, the proportion of copper must be reduced, otherwise the metal cracked during working.

20. Rufus (1900) gives from .4 to .5% copper as the limit beyond which red-shortness is produced.

21. Stead and Evans (1901) investigated the influence of copper on steel rails and plates. Four series of Bessemer steel rails were made containing respectively about 0.5, 0.9, 1.3 and 2.0% Copper. One open-hearth charge was also experimented upon, this charge having had added about 0.5% copper. In each trial the fluid charge of the liquid steel in the ladle was divided into two parts, to one of which was added the copper. This method was chosen to get a good comparison of the copper steel with that to which none was added. In all cases the cold copper ingots when thrown into

the liquid steel readily melted and mixed most perfectly with it. In no case did it deaden or make the steel more lively in the molds.

In every parallel case the steels containing copper rolled as perfectly as those without it, with the exception of the steel containing about 2.0% copper, which was torn on the flanges. An examination of these finished rails showed the defect to be due to over-heating; the heads, however, were perfect, and after being slotted off, were reheated and rolled into wire rod without cracking or breaking up in the least degree. The companion ingots without the copper were not over-heated. We (Stead and Evans) conclude from this that steel with very large percentages of copper, although not red-short in the ordinary sense, will not bear the same amount of heat as when copper is absent, and that its effect in this respect resembles that of carbon and not of sulphur.

A remarkable result was obtained with open-hearth steel to which 0.5% copper had been added. In rolling the non-cuprous part, every ingot cracked perceptibly, whereas the same steel containing copper rolled without a flaw. The tensile tests on these heats are shown below.

Average results - Copper steels.

	T. S. Tons per sq. in.	E. L. Tons per sq. in.	Elong. in 2". %	Contraction. %	Carbon %
Series No. (1) 0.60% Cu.	46.55	25.00	19.30	21.38	42
" " (2) 0.889% Cu.	49.4	27.1	23.0	37.0	49
" " (3) 1.286% Cu.	42.0	28.0	23.0	35.0	32
" " (4) 2.00% Cu.	49.7	35.9	21.5	35.4	30
	COPPER-FREE STEEL.				
1	44.63	25.20	20.66	27.56	42
2	48.00	24.80	21.00	32.00	49
3	41.6	23.4	26.00	39.5	32
4	39.7	22.1	27.00	41.00	30

The above specimens were taken from the rail sections and not annealed. The average results on the annealed rails are given below.

Annealed Rails.

	Tensile Strength. Tons per □"	Elongation in two (2) inches. In.	Contraction %
Cuprous	47.35	19.75	35.87
Normal	41.80	24.50	41.30

The tensile strength tests on the acid open hearth trials showed no marked difference in either strength, elongation or contraction. The elastic limit was not given.

Among other conclusions which Mr. Stead and Mr. Evans arrived at is the following:- "In small quantities copper slightly raises the elastic limit and tenacity, but, unlike phosphorous, does not sensibly make the steel liable to fracture under shock." They arrived at this conclusion from the data obtained on dropping a one-ton weight on the rails. This test showed the ones containing copper to deflect equally as well as those without it, and also that the ones with 2.0% copper which had flaws on the flanges were broken by the second blow. The rails in series I, II and III were 90 lbs. to the yard and of full head section, while No. IV was a flanged series of 56 lbs. per yard. The weight of 1 ton was dropped 20 ft. in the first three series and 15 in the fourth.

22. Stead and Wigham investigated the influence of varying amounts of copper on steel for wire drawing. Their data, upon inspection, shows copper to have no beneficial effect, and in several instances it was observed that the copper steel wire was much lower in tensile strength. Their researc on this subject was not of such nature to lead one to believe absolutely that small percentages of copper are detrimental in wire making, yet they conclude that for wire making where the carbon is 1% or thereabouts, copper should be avoided.

23. Campbell (1907) says that most of the Bessemer and open-hearth steels mentioned in his book contained from 0.3 to 0.5% copper. "This will be sufficient proof that the best steel may contain up to 1.0% copper without being seriously affected, but if at the same time sulphur is high, say .08 to .1%, the cumulative effect is too great for molecular cohesion at high temperatures, and it cracks in rolling." He found no difference in the ultimate strength of steels with high or low copper content. "The high copper gives a slightly higher elastic ratio which is a benefit and a better elongation and reduction of area."

24. Breuil. (1907) The present work of Mr. Breuil, to be herein described, represents one of the most extended investigations on the effect of copper on the properties of steel. He studied

<u>1st.</u> A mild steel, Series A, containing carbon approximately .15% and copper 0, 0.49, 1.005, 2.015, 3.99, 8.05, 15.97 and 31.92%, respectively.

<u>2nd.</u> A semi-mild steel, Series B, containing carbon approximately .35% (.28 - .41 being the most extreme limits) and copper approximately the same as in Series A.

<u>3rd.</u> Hard steel, Series C, with carbon about .56% as an average, and copper the same as in Series A and B.

The ingots cast were about 110 lbs. weight and the shape of a truncated pyramid. 33 pounds was cropped from the top and 11 from the bottom of each ingot. Upon cropping the ingots they were cut so as to leave a considerable portion of metal, and then broken. The object was to study the fracture.

In each ingot the percentage of copper at the base and near the top was determined, while the other constituents were determined but once.

Chemical analysis and the fractures showed at once that when the percentage of copper was less than 4, there was no segregation, no matter what the carbon content might be.

Owing to the fact that the steels of higher copper content being of no particular practical value, and for the sake of brevity, only those steels with from 0. to 4.0% copper will be considered in detail.

Ingots containing less than 8.0% copper showed no coloration at their fractures.

The ingots of Series A and B containing less than 4.0% copper were the only ones capable of being rolled. The remainder were red-short and fell to pieces when forged.

Critical points determined by the usual method seems to indicate no distinct change of the Ar_3 and Ar_2 points in Series A (mild steel series) with copper up to 8.0%. In Series B, with no copper present, the Ar_1 point occurs at 720°C. while with 16.0% copper it occurs at 630°C. In Series C the Ar_1 point occurs in all the steels between 570°C. and 600°C. Thus it seems that copper does not lower the Ar_1 point below 550°C.

The bars containing less than 4% of copper, after rolling were tested mechanically, after being treated as follows:-

1.	Bars as rolled (untreated)		
2.	Annealed at 900°C.	(Series A and B)	
	" " 830°C.	(" C)	
3.	Quenched at 870°C.	(" A and B)	
	" " 830°C.	(" C)	
4.	Quenched at 870°C.,	drawn at 800°C.	(Series A & B.)
	" " 830°C.,	" " 350°C.	(" C)

Tensile Tests.

The tensile specimens were 13.8 millimeters in diameter and 100 millimeters long. All the bars of Series A (low carbon) behaved well on quenching. Series B, were somewhat warped. Series C, except the one with 0.5% copper, cracked more or less on quenching. A table of the results is on page 17 of the Journal of the Iron and Steel Institute, No. II, 1907.

In the rolled condition the yield point and tensile strength appear to increase as the copper content increases. This is also true of the quenched specimens. It is true of the annealed specimens also, though not nearly to so great an extent. In the table it is clearly shown that copper greatly increases the strength of the rolled material. Striking results are also to be found in the quenched specimens.

Mr. Breuil states as follows:- "Nevertheless, it is possible to perceive, by considering only the steels in their untreated state, that the copper steels obtained by the author are equal to, for example, nickel steels, from the point of view of tensile strength, They generally possess a higher elastic limit and maximum strength than the latter."

From studying the untreated bars Mr. Breuil notes that copper has a more active influence on steel than nickel, manganese or chromium, and approaches than of vanadium. The annealed steels, however, do not bear out this statement.

By comparing the data on some of Hadfield's tests on nickel steels with those of Breuil on copper steels, it is found that steels containing copper are closely comparable to steels containing nickel or chromium of the same carbon content, and follow the same laws in respect to their increased tensile strength with increased percentages of copper.

Wigham has found that with wire containing increasing percentages of copper, but not exceeding 1.0% of that metal that the tensile strength increases with the % of copper, although only slightly when the steel has been annealed.

Shock tests.

These tests were carried out first by the notched bar method, and second by the plain bar method. (Not a Charpy test) The actual work done in breaking a given section of the bars was calculated in each case. Results in the form of a table showed the maximum resistance for (1) the annealed bars, Series A, to be 4% Cu.; (2) the rolled bars A 0.0% Cu. and A 0.5% Cu.; (3) the quenched bars A 0% Cu. with A 0.5% Cu. closely approximating A 0.0; and (4) the quenched and drawn bars, A 0% Cu. with A 0.5% Cu. approximating A 0.

In Series B, B 0.5 shows the greatest resistance to shock in the rolled bars. In all the others B 0 is strongest, with the rest decreasing in their shock resisting power as the copper increases. In Series A the quenched and quenched and drawn specimens give high resilience as compared to the rest.

It is not possible to give any definite decision based on these tests, however, since the shock test of this kind is not very reliable. In some instances the steel containing copper was greatly superior,in regard to the shock resisting power, to those without copper.

The Brinell hardness number in all cases, rolled, annealed, quenched, etc. increased as the copper content increased. The ordinary Brinell machine with 10 mm. ball and 3000 kgs. wt. was used.

Microscopic examination was made and several microphotographs submitted with the paper. Copper seems to retard the formation of pearlite, thus making the steel appear more sorbitic, and it also produces a tendency toward a finer grain.

Corrosion Tests.

A great many corrosion tests have been made upon copper steels both by Mr. Breuil and others. All the investigations seem to indicate that copper is beneficial in reducing corrosion.

Torsion tests were made on a Wicksteed machine. The data obtained shows that the law of the increase in resistance to torsion is exactly the same as that of the resistance to tensile stress, so far as copper was concerned, the total angles of torsion causing fracture corresponding approximately to the elongation.

Some conclusions which may be drawn from this investigation are:- (1) Copper steel does not yield a metal capable in practice of being rolled if the percentage of copper exceeds 4.0%; (2) as regards tensile strength, the copper steels appear stronger(when in the rolled condition) in proportion as they contain more copper, the difference being more manifest in proportion as the carbon is lower; (3) Annealing leaves the steels with the same characteristics but greatly reduces the differences observed in the untreated (rolled) bars.

Mr. Breuil also concludes that copper steels equal nickel steels in view of tensile strength, and that copper steels are no more brittle than nickel steels containing equivalent % of nickel. These conclusions are in agreement with those arrived at by Mr. Stead on this same subject.

Mr. Breuil next investigated the influence of copper on steel with 1% carbon. The tests described in the former experiments were carried out here also. The table of properties shown by the tensile test is given below.

Treatment.	Nature of steel	Apparent E. L. per □ mm. Kgs.	Maximum strength. per □ mm. Kgs.	Elong. % before fracture	Cont. of area. %	Actual Breaking STRENGTH per □mm	Remarks
As rolled.	D 0.% Copper	63.8	88.4	9.0	0.15	87.0	Broke normally
	D 0.5% "	71.1	102.8	5.5	.04	103.0	Broke near hea
	D 1% "	69.3	111.0	6.0	.07	110.0	Broke normally
	D 3% "	97.5	117.0	1.5	.01	118.0	Broke near hea
Reheated to 825°C.	D 0% Copper	45.1	71.4	20.0	.39	90.0	
	D 0.5% "	48.0	79.4	16.2	.34	97.0	Broke
	D 1.0% "	56.5	80.0	16.5	.32	99.0	normally
	D 3.0% "	63.7	84.0	13.6	.43	81.0	
Quenched at 825°C., Hot water.	D 0.% Copper	70.0	93.0	8.6	.22	110.0	Broke
	D 0.5% "	76.0	108.0	8.2	.27	110.0	normally
	D 1.0% "	70.0	92.5	8.0	.31	103.0	Broke
	D 3.0% "	86.8	107.6	4.05	.17	123.0	near hea

These tensile bars were of the same dimensions as those used in the former tests, viz: 13.8 mm. diameter and 100 mm. in length.

The data presented on the shock tests of this steel did not show any noticable decrease or increase in shock resistance by increasing copper percentage, and it thus appears that copper steels containing 1% of carbon show no more brittleness than those without it.

The Brinell hardness tests may be briefly noted in the following table of results.

	Steel as rolled.	Reheated to 825°C.	Water quenched at 825°C. (Hot water)
D 0.0% Copper	302	217	332
D 0.5% "	286	235	332
D 1.0% "	364	277	311
D 3.0% "	375	277	311

The most recent extended investigation of the effect of copper on steel is that of Clevenger and Ray, which will now be described.

Experimental.

MAKING INGOTS. "Small, circular, oil fired furnace used, (using low pressure burner), to heat the No. 25 graphite crucibles in which the steel was made. Material: (1) Mild steel punchings .23% C.; (2) best grade of electrolytic copper; (3) 80% Ferro-manganese; (4) a good grade of commercial aluminum. 30 lbs. of punchings charges in crucible and melted. Then "killed" for 20 to 25 minutes. Then 2.5 ounces of ferro-manganese was added and stirred well. 5 to 7 minutes later the required amount of copper was added and again stirred. About 5 minutes later 0.096 oz. aluminum was added and after again stirring, the metal was poured into a previously heated ingot mold. Sufficient slag was added to each charge to form a protective coating over the molten metal. This was done to prevent the absorption of gases. At first sound ingots were hard to get, but by carefully following the above outline this difficulty was eliminated. Thorough investigation on this topic was not made, but we were lead to the following conclusions in regard to making sound ingots:- (1) thoroughly kill the metal before adding the copper, (2) add some deoxidizer, as Aluminum, just before pouring."

"Each ingot weighed about 30 lbs. and was 3" x 3" x 12". Eight (8) ingots were made. An attempt was made to keep everything constant in the composition except the copper. The copper was intended to be as follows:-

A 0 - .00%,
A 0.25 - .25%
A 0.5 - .50%
A 1 -1.00%
A 2 - 2.00%
A 3 - 3.00%
A 4 - 4.00%
A 5 - 5.00%

All were sawed to a depth of 1" on two opposite sides, 2" above the bottom. After breaking, a fracture approximately 1" x 13" was shown. In sawing and breaking, the following was observed:- A 0, soft and tough, about like machine steel. The brittleness became more evident with increasing copper, except in A 5, which had a coarser grain than any."

"Segregation was not noticeable to the eye in any. All were white, lustrous, and uniformly grained in fracture. There were reddish streaks of Copper Oxide in the form of very thin films on the surfaces of A 4 and A 5. The slags from the high copper steels were slightly tinged red from copper oxide, it was thought."

"FORGING. All were heated in a large forge and reduced to 1-1/8" octagonal bars by the steam hammer. All forged about like ordinary machine steel. A 2 seemed somewhat softer than the rest. A 5 showed red shortness, and after cooling the surface showed minute cracks."

"WELDING" Lap welds were tried upon the eight bars with the following results:- A 0 seemed to weld perfectly at a bright red heat, almost yellow, similar to machine steel." A 0.25 appeared rather over-heated but welded easily. A 0.5 could not be welded with the hand hammer at yellow heat, and welded with difficulty under the drop hammer at bright yellow. A 1 welded fairly well under drop hammer at bright yellow. A 2, at bright yellow, scintillating, welded with difficulty under drop hammer. A 3 could not be welded at any heat from red to almost white. A 4 - the ends slipped off and crumbled to pieces at bright yellow under the drop hammer. Metallic copper showed on the surface of the heated ends when cold. A 5 - the ends did not stick at any heat, 'resisted all attempts to weld; copper showed on surfaces of heated ends as in A 4."

"Test pieces were turned from the welded specimens and the breaking strength determined.

Marks	Breaking Strength: Lbs. per sq. inch	Fractured.	Breaking Strength of unannealed specimens. Lbs. per sq. in.
A 0	22,300	86,700	Along weld.
A 0.25	25,500	99,500	" "
A 0.50	88,200	99,000	Along & across weld.
A 1	83,000	97,400	" " " "
A 2	39,600	120,600	Along weld.

Analysis. Copper, sulphur and carbon only are given here, other elements O.K.

Marks.	Copper %	Carbon %	Sulphur %
A 0	.00	.46	.038
A 0.25	.165	.60	.029
A 0.5	.493	.52	.039
A 1	.846	.45	.036
A 2	1.857	.53	.022
A 3	2.773	.43	.020
A 4	3.574	.44	.021
A 5	4.512	.46	.019

Here and in other papers along this line it seems that copper has a tendency to decrease the sulphur.

A 1 shows (by chemical analysis) that the copper has a slight tendency to segregate. A 3, more marked, and in A 5 it was serious. The copper tends to segregate to the bottom. Breuil (Journ. Iron & Steel Inst., 1907, II, p. 6) noticed the same thing only that segregation did not take place till over 4% copper was present. He also found that high copper steel had a tendency to form a copper-rich core with a shell of low copper content. Stead says- "It was found that steel with 1% Carbon would dissolve and retain in solution 7% of copper" but that when this much was exceeded the copper separated out as globules.

Corrosion tests in 1-3 H_2SO_4 gave the following results:-

Sample	Copper	% loss by corrosion.
A 0	0.00	22.20
A 0.25	.165	7.14
A 0.50	.493	5.35
A 1.	.846	6.93
A 2	1.857	11.31
A 3	2.773	32.60
A 4	3.574	37.00
A 5	4.512	42.60

Sample A 0 was badly pitted while all the copper steels were corroded smoothly.

Walker (Met. & Chem. Eng., Sept., 1911) points out that there many steels which did not resist atmospheric corrosion and did resist acid corrosion were found to contain copper.

Williams (Iron Age, 1900, Nov. 29) dipped Bessemer steel and wrought iron in water frequently and let dry in air. They contained copper. As the copper increased the corrosion decreased.

Buck (Journ. of Indust. & Eng. Chem., June, 1913) made elaborate and convincing investigations on the effect of copper on corrosion. His steels contained 0.15%, 0.24% and 0.34% copper, respectively. It was made in corrugated sheets and placed (1) on roof in Pennsylvania coke [illegible] where the air contained sulphuric and sulphurous acid vapors, (2) at the sea-shore, and (3) in a rural district free of corrosive agents. "In every case the steel with copper additions have shown marked resistance to corrosion as compared with non-copper steels, having on the average nearly twice the life." All results seem to point to a beneficial effect of copper in regard to retarding corrosion.

Microstructure. Two series of specimens were prepared,** one as forged and another after annealing the forged specimens at 820°C. All were etched with 10% HNO_3 in alcohol and photographed at Sauveur & Boylston's, Cambridge, Mass. In the specimens as forged, the ferrite is permeated with filaments of cementite, more or less in proportion to the copper content. Large patches of free ferrite appear in the specimens with decreasing copper content and the pearlite is less evenly distributed. In the annealed specimens the effect of copper is not so marked in this respect. With rapid or fairly rapid cooling, copper seems to promote the formation of a finer grain. This is also not so visible in the annealed specimens. Up to a certain limit, copper forms a homogeneous alloy with iron, but beyond this the copper begins to envelope the grains of ferrite. Stead says the copper is in solution till over 8% is reached.

The amount of copper which will harden the ferrite will depend upon the amount of iron which remains in excess of that needed to form cementite with the carbon. Hence, all other conditions being equal, as the amount of carbon increases, the less copper it is capable of absorbing. Stead found (Idem, p. 112) that when copper was in excess of that soluble it formed at the boundary lines of the grains and that fracture followed the boundaries, thus the envelopes of copper are a source of weakness. Breuil says the presence of copper increases the pearlite in steels, and to some extent causes

** [illegible]

the steel to be more highly carburized, and thus harder. With copper up to 4%, these steels contain no free copper, it all being in solution in the iron.

Copper acts in two ways:- (1) it tends to distribute the carbide more evenly, thus tending to produce a finer grain, (2) it hardens the ferrite by forming an iron copper alloy which is harder than pure iron. According to Burgess and Aston, the structure of copper steels "is a fine pearlite with a fibrous cementite, which is liberated with increasing copper. This explains the increasing hardness. The hardness does not result from lowering the critical range.

<u>Critical points.</u> Critical points were determined. The Ar_1 is lowered from 736°C. in A0 to 644 in A5. Breuil says "Copper lowers the recalescence point in steel, but not below 550°C." Muller found the arrest points in iron to be lowered 60° to 80° by copper.

<u>Tensile tests.</u> Tensile tests were taken (1) as forged, (2) forged and annealed. The results of the tests are more easily seen by observing the following table.

<u>Forged.</u>

Marks	Copper %	E. L. lbs. per sq. in.	T. S. Lbs. per sq. in.	Elong. %	Cont. %	Breaking Strength. lb. per □"	Remarks.
A 0	0.	51,600	86,700	20.0	33.2	Same	
A 0.25	.165	53,300	97,800	10.0	6.1		
A 0.50	.493	60,300	99,000	17.5	21.7	as	
A 1.	.846	60,300	97,400	20.0	29.3		
A 2.	1.857	84,000	120,660	10.0	4.0	tensile	
A 3.	2.773	94,600	124,300	10.0	12.3		
A 4.	3.574	100,500	111,300	2.5	.80	strength.	
A 5.	4.512	124,400	134,000	2.5	3.54		Flaw in center.
			ANNEALED SPECIMENS.				
A 0	0.	39,000	75,200	25.0	54.20	62,000	
A 0.25	.165	48,300	93,500	16.25	48.25	80,600	
A 0.50	.493	49,000	94,000	20.00	31.40	87,900	
A 1.	.846	55,000	87,150	15.0	37.6	79,400	Showed flaw after breaking.
A 2.	1.857	61,700	96,600	13.70	37.9	88,350	
A 3.	2.773	66,000	80,000	16.35	38.4	84,300	
A 4.	3.574	68,000	99,980	16.25	37.0	90,260	
A 5.	4.512	74,200	110,000	17.5	43.8	85,300	

In general these results agree closely with those of other investigators and point to the fact that the ultimate strength is in almost direct proportion to the copper content. Other properties (elong. and contraction, etc.) can be seen from the table.

Hardnesses as given by the Shore Scleroscope are:-

A 0 = 28	A 2 = 37
A 0.25 = 31	A 3 = 37
A 0.50 = 29	A 4 = 40
A 1 = 28	A 5 = 43

The hardness is supposed to be due to two effects that the copper has, viz:- (1) it retards the formation of pearlite and hence there is more diffused cementite, thereby making the constituents of the steel finer; (2) it hardens the ferrite by alloying with it.

Burgess & Aston found no change in the electrical conductivity up to 7.0% copper in copper-iron alloys. With over 90% the conductivity is increased. Small amounts of iron greatly decrease the conductivity of copper.

Fric found that copper increases the resistance up to a certain point, then it ceases to do so.

Dillner found the magnetic properties not affected by .64% copper.

Conclusions

1. In making copper steel by the crucible process it is necessary to "kill" the metal before adding the copper, and just before pouring it is advisable to add a small amount of some deoxidizing agent.

2. In forging the ingots containing from 0.437 to .605% carbon, traces of red shortness began to be shown with a copper content of 4.512%. Up to this point the steel forged about like machine steel.

3. Up to 0.846% copper our steels gave satisfactory welds. At 1.857% copper the weld was much weaker and above this point the steel was not to be welded.

4. There appears to be a marked tendency for copper to eliminate sulphur.

5. In the series of steel studied the segregation of copper toward the bottom of the ingot begins to be slightly noticeable with 0.846% copper. With 2.773% the segregation is more, and with 4.512% it is very marked.

6. The presence of small percentages of copper up to 0.493% has a most marked effect in preventing the corrosion of steel in dilute H_2SO_4. As the percentage of copper increases, the loss by corrosion increases until with 2.773% the loss is greater than with no copper at all.

7. As the percentage of copper increases the structure becomes finer, due to the more even distribution of fibrous cementite. This is more apparent in the forged than in the annealed specimens.

8. The Ar_1 was lowered from 730°C. in 0% Copper to 635°C. in the 4.512% copper steel.

9. The elastic limit in both the annealed and unannealed specimens

increases steadily until with 4.512% Copper it was increased more than 100% over the steel with 0.% copper.

Within the limits of this investigation, the ultimate strength seems to increase in almost direct proportion to the copper increase.

With the unannealed specimens the actual breaking strength in all cases was the same as the ultimate strength. The actual breaking strength in case of the annealed specimens shows an increase with increase of copper. In the annealed, the elongation is somewhat irregular, but in general decreases up to 1.857% copper and then increases, reaching a maximum at 4.512% copper. The general tendency in the annealed is to decrease the elongation up to 1.857% copper and then increase it to 4.512%. In the unannealed, the general tendency is to decrease the elongation throughout the series.

10. The hardness of the steel increases with increased copper content and corresponds fairly well to the tensile tests.

The following letter from Dr. P. H. Dudley to the Commanding Officer, Watertown Arsenal, (W.A.47.14/56) contains much information which is of interest, particularly so as a great deal of the data has not heretofore been made public.

"I rolled from 1891 to 1898, about 500,000 tons of rails which contained from six to eight tenths of one per cent of copper. The rails which I rolled in 1891 at Bethlehem, contained copper but the content was not as high as the rails mentioned which I rolled at Scranton. These were all Bessemer rails and was partly made from the Cornwall ore from Lebanon, Pa. The copper is contained in the ore, associated with phosphorous .015. These rails at both Bethlehem and Scranton were made under the drop test, from which we obtained from twelve to sixteen percent exhausted ductility. The phosphorous allowed in the rails was .06, the carbon ranging from .56 to .65, though in some of the 100-lb. rails at Scranton, the maximum carbon was as high as .68. The copper evidently did not detract from the ductility of the metal and we obtained elastic limits from 55,000 to 65,000 pounds in tensile tests. The rails after fifteen to twenty years service show but a limited amount of oxidation."

"The rails were rolled mostly in three rail length ingots for 30-ft. rails and the top rail was lettered "A", the next rail in the ingot "B" and the last one "C". It was found in service that the "A" rails wore slightly more rapid than the "B" and "C" rails. We could also see on the inside corner of the head that there was more spawling off of pieces from two to three inches in length than on the "B" and "C" rails. Part of this was due to a slighter higher percentage of impurities in the "A" rail than in the lower parts of the ingots. The steel in ingots of fourteen to sixteen inches on the base, cast solid, the shrinkage cavities in cold ingots hardly show more than a trace."

"There has not been any detailed technical account of these rails published to date."

"I should be pleased to arrange to secure for you pieces of some of the Bethlehem and also the Scranton rails for your tests should you so desire."

"I had made one or two experiments with Bessemer steel, putting into the converter a few pounds of copper. I was not able to be present when the experiments were made, but the mill pronounced them failures as we did not obtain only a trace of copper in the heat. We have made a few experiments of putting about .25 of 1% of copper in tie plates to resist corrosion, which shows quite a decided lessening of the oxidation for those plates compared to open hearth steel."

"The breakages of the .06 phosphorous and high carbon rails mentioned, with the content of copper showed but a very few breakages in the track, and out of all the rails I only know of 25 cases of split heads after their many years of service. We should like to make rails at the present time with a content of copper in the ore for our results of the rails in service show that it was beneficial rather than detrimental."

Prof. Carle Hayward, of Massachusetts Institute of Technology, recently carried out some work on the effect of copper in steel in which the Charpy machine at Watertown Arsenal was used to determine the shock resisting power of the two materials used. The analysis of these two steels was as follows:-

	# 41-42-43	51-52-53-54
Carbon	.380	.365
Phosphorous	.012	.053
Manganese	.57	.59
Sulphur	.030	.048
Copper	.86	.03

These specimens were tested in the forged condition, annealed, and after various heat treatments. His results indicate that the Charpy figure was higher for the steel containing .86% Copper. Examination of his analyses will show, however, that the steel containing .86% Copper had a Phosphorous content of .012%, whereas the steel containing .03% Copper had a Phosphorous content of .053%. In other words, the variation in Phosphorous is such that no reliance can be placed on the effect of copper in increasing the shock resisting power of the two steels which he used.

Lt. J. B. Rhodes, of the United States Navy, recently carried on some work in which copper was introduced into the metal in the form of monel metal, which is an alloy of copper and nickel. His steels are essentially high manganese steels containing over 1% of nickel and from .25% to .80% copper. The results obtained were very favorable. No blank heats were run which contained high manganese, and a small amount of nickel so that it was impossible to say with any certainty what the influence of copper was.

Respectfully,

F. C. Langenberg,

Metallurgist.