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Effect of Copper and Silicon on Selected Mechanical Properties of Hot-Rolled Medium-Carbon Steels

UNITED STATES DEPARTMENT OF THE INTERIOR

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Effect of Copper and Silicon on Selected Mechanical Properties of Hot-Rolled Medium-Carbon Steels

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EFFECT OF COPPER AND SILICON ON SELECTED MECHANICAL PROPERTIES OF HOT-ROLLED MEDIUM-CARBON STEELS

by

Mark I. Copeland[1]

ABSTRACT

The Bureau of Mines investigated the effect of up to 1 wt-pct of copper and silicon on the heat treatment response and hardness, tensile, and impact properties of hot-rolled medium-carbon steels. The steels were prepared by induction melting and fabricated into plates by forging and rolling. The tensile strength of 0.2-wt-pct carbon steels containing 0.3 wt-pct silicon was affected significantly by copper in both the hot-rolled and heat-treated (600° C) conditions, whereas the tensile strength of the 0.3-wt-pct carbon steels was less affected. A 600° C treatment was considered optimum as a post-rolling treatment to strengthen the steels by copper precipitation. Strengthening of 0.2-wt-pct carbon steels by silicon was reduced by increasing copper contents. Optimum impact strengths occurred at about 0.3 wt-pct silicon in 0.2-wt-pct carbon steels containing 0.6 and 0.8 wt-pct copper. The impact strengths were lowest for 0.2-wt-pct carbon steels containing over 0.8 wt-pct copper and greater than 0.3 wt-pct silicon, especially in the heat-treated condition. Copper and silicon solutes and copper precipitates strengthened the steels. This effect was augmented slightly by strengthening through grain refinement by these solutes.

INTRODUCTION

Copper contamination of ferrous scrap is a growing problem in the steel industry. Copper, a residual element, is not removed as an oxide in the slag during steelmaking as it has a smaller negative free energy of oxide formation than iron. Because of this factor and because copper components in scrapped automobiles are too expensive to remove completely, the copper content of ferrous scrap increases with time.

Copper contamination causes surface hot-shortness during hot fabrication, and when copper-bearing steel is heated in oxidizing gases, copper normally accumulates on the steel surface under the scale. Molten copper penetrates and weakens the steel grain boundaries during hot fabrication and may cause deep cracks, particularly on the edges of flange sections where tensile stresses occur. Nickel additions are known to prevent formation of copper

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on the surface when steel is heated. However, the use of nickel in carbon steels has been very limited because of its high cost.

In view of the surface hot-shortness problem, the Bureau of Mines conducted an earlier study (4)[2] to determine if silicon additions, which are relatively inexpensive, could be used to prevent the formation of copper on the steel surface during heating. Prevention of copper formation by the use of silicon was found to occur under specific conditions when molten fayalite (Fe_2SiO_4) formed on the steel surface by internal oxidation. When 1-wt-pct copper steels were heated to 1,300° C in atmospheres containing 2 vol-pct excess oxygen (simulating industrial ingot reheating practice), up to 1 wt-pct silicon was necessary to prevent copper formation. The amount of silicon required decreased with decreasing copper content of the steel and increasing oxygen content of the furnace atmosphere.

The present study was primarily conducted to determine the effect of up to 1 wt-pct silicon on selected mechanical properties of hot-rolled steels containing up to 1 wt-pct copper. There is an abundance of information on the separate effects of copper (7, 13) and silicon (8), but not of the two together. Most other reported studies were conducted on normalized, normalized and aged, or austenitized, quenched, and aged steels, but not on hot-rolled steels. If up to 1 wt-pct copper and silicon proves to be innocuous to the properties of hot-rolled steels, the use of silicon additions to prevent surface hot-shortness by copper may become acceptable by industry.

Copper may strengthen steel by both solid solution and precipitation hardening. Solution hardening by copper is similar to that by nickel, and is relatively small compared with hardening by equivalent contents of manganese and silicon (12). The cooling rates necessary to hold copper in solution are relatively low: the final hardness is not greatly affected unless the cooling rate is less than 90° C per hour (14). The most marked increase in strengthening by copper precipitation heat treatments occurs when the copper content exceeds 0.9 wt-pct (13). The copper precipitates, sometimes referred to as epsilon copper, contain about 0.30 wt-pct iron at 600° C (10). Precipitation heat treatments of 480° to 600° C are usually used. Copper in amounts of 0.9 to 2.0 wt-pct can result in tensile strength increases of up to about 20,000 psi following heat treatment for appropriate times in the precipitation-hardening temperature range. Precipitation strengthening is characteristically accompanied by a decrease in toughness, particularly in notch-impact resistance.

Although silicon is primarily a solid solution strengthener, it may influence precipitation hardening by copper. According to the data of Halley (9), silicon has a marked effect in increasing the time for precipitation hardening by copper at all temperatures. These data conflict with data of Smith and Palmer (14).

For our investigation, selected mechanical property tests were conducted on steels in the hot-rolled and aged conditions. Of special interest were the

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[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

properties in the hot-rolled condition, as the bulk of the carbon steels of industry are marketed in this condition. Copper precipitation hardening (aging) studies were also conducted to determine if substantial benefits may be derived by the technique, even if most steel mills do not presently use a post-rolling heat treatment. Heat treatment temperatures that would give substantial strengthening increases in as short a time as possible were selected, because time is a costly factor in steel mills. After rolling and cooling to a specific temperature, the hot steel may be charged directly into a heat-treating furnace for copper precipitation strengthening. The strength data were conpared with each other, not with published data. Comparison of strength properties with published data could be misleading, as the strength of steels is somewhat dependent upon steelmaking practice, which is usually different than that used in the present study. Because of strength dependency on steelmaking practice, the steels used in this study were prepared as uniformly as possible.

Tests were conducted on induction-melted steels that were forged and rolled. Copper precipitation treatments on the hot-rolled steels were conducted at 500°, 600°, and 650° C for up to 8 hours in air. Room temperature hardness, tensile, and impact tests were used for evaluation of strength properties. Visual and electron-microscopy studies as well as thin-section examinations were also conducted.

ACKNOWLEDGMENTS

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PROCEDURE

Five series of steels were prepared as follows: Series I and II were made for comparing the effect of copper on steels containing 0.2 and 0.3 wt-pct carbon; and series III, IV, and V were used for evaluating the effect of both copper and silicon on steels with 0.2 wt-pct carbon. The target compositions are given in table 1 and actual analyses are shown in table 2. The sulfur and phosphorus contents, which are not listed, varied between 0.013 to 0.018 wt-pct.

TABLE 1. - Target chemical composition of steel heats

	Content, wt-pct			
	C	Mn	Si	Cu
Series I..................	0.18-0.23	0.35-0.55	0.25-0.45	Up to 1.0
Series II..................	.28- .33	.35- .55	.25- .45	Up to 1.0
Series III................	.18- .23	.35- .55	Up to 1.0	0.55-0.65
Series IV..................	.18- .23	.35- .55	Up to 1.0	.75- .85
Series V...................	.18- .23	.35- .55	Up to 1.0	.95-1.05

TABLE 2. - Chemical analyses of steel heats

Series and target composition	Heat	Content, wt-pct			
		C	Mn	Si	Cu
Series I: Varying Cu contents and 0.2 wt-pct C.	121	0.22	0.38	0.25	0.12
	112	.22	.42	.40	.22
	122	.20	.38	.25	.40
	113	.20	.45	.35	.85
	115	.18	.45	.28	1.09
Series II: Varying Cu contents and 0.3 wt-pct C.	120	.33	.46	.40	.28
	123	.28	.35	.30	.50
	124	.33	.35	.45	.60
	125	.30	.41	.38	.85
	126	.32	.36	.42	1.01
Series III: Varying Si contents, 0.2 wt-pct C, and 0.6 wt-pct Cu.	138	.21	.42	.18	.56
	137	.22	.38	.30	.55
	145	.18	.46	.58	.53
	141	.20	.50	.84	.57
	143	.19	.55	1.12	.57
Series IV: Varying Si contents, 0.2 wt-pct C, and 0.8 wt-pct Cu.	146	.22	.30	.19	.83
	147	.21	.42	.27	.80
	148	.21	.46	.58	.84
	149	.21	.54	1.13	.82
Series V: Varying Si contents, 0.2 wt-pct C, and 1.0 wt-pct Cu.	115	.18	.45	.28	1.09
	119	.18	.42	.42	1.00
	117	.19	.40	.58	1.05
	118	.22	.52	.72	1.02
	135	.23	.46	1.18	1.02

The 24 heats, weighing 65 lb each, were prepared by induction melting of SAE-1020 steel bar stock. Argon flowing under a graphite crucible cover was used to reduce oxidation of the heat additions. As the charge was being heated to the pouring temperature (1,600° C), copper, carbon, manganese, and silicon were added in that order as copper wire, pig iron (carbon), ferromanganese, and ferrosilicon, respectively. When necessary, the heats were killed with aluminum immediately before pouring into tapered, hot-topped molds with 4-inch-square cross section. The amount of aluminum was progressively reduced from a maximum of 2 pounds per ton, and none was added for heats containing more than about 0.7 wt-pct silicon.

After removal of the hot tops by sawing, the ingots were heated, forged, and rolled. The cold ingots were heated to 1,250° C in 2 hours, soaked for 1 hour, and then step-forged on one side to a 3-5/8-inch thickness, the maximum opening for the two-high rolling mill. After forging, the ingots were immediately reheated to 1,250° C for 1/2 hour and then rolled to plate by the following schedule:

Pass	Thickness, inches		Reduction per pass, percent
	Initial	Final	
1......................	3.60	3.20	11.1
2......................	3.20	2.75	14.1
3......................	2.75	2.40	12.7
4......................	2.40	1.90	20.8
5......................	1.90	1.50	21.0
6......................	1.50	1.05	30.0
7......................	1.05	.75	28.6
8......................	.75	.60	20.0
9......................	.60	.50	16.7
10.....................	.50	.30	40.0
11.....................	.30	.20	33.3

After the 9th rolling pass, the 1/2-inch-thick plate was sawed transversely into two equal sections. One section was reheated at 1,200° C for 30 minutes and rolled in two passes to a 1/5-inch thickness and a width of 5-1/4 to 5-1/2 inches. The temperature of the plate, after rolling passes 9 and 11, was 850° to 875° C. The total rolling time, except for the cutting and reheating steps between passes 9 and 10, was close to 2-1/2 minutes. All operations were kept as uniform as possible so that the mechanical properties of the rolled steels could be compared by composition and structure rather than by the processing. After rolling, the steel plate was cleaned by sandblasting.

Initially, the effects of copper precipitation heat treatments at 500°, 600°, and 650° C on hardness were studied on sections of plate made from four heats. The studies would prove helpful in determining the post-rolling heat treatment to use on the steels and in evaluating the effect of composition on hardening by precipitation. Sections 1/2-inch square were cut from 1/5-inch-thick plate and the rolled surfaces were sanded to remove the decarburized layers. These sections were heated for time periods up to 8 hours in an argon atmosphere, air-cooled, sanded, and then tested for Rockwell B hardness.

Tensile tests were conducted on specimens made from 1-inch-wide by 5-inch-long sections cut from the 1/5-inch-thick plate. Two specimens were cut with the major length parallel to plate rolling direction (longitudinal) and two were cut transversely for both the as-rolled and aged conditions. When aged, the sections were heattreated before making into tensile specimens. The sections were heated in air at 600° C for 30 minutes. Ten minutes of the time was required for heating to 600° C, as determined by a thermocouple spot-welded to the section. The gage section of the test specimens was 2-3/4 inches long and 0.250 inch ± 0.005 wide. At a strain rate of 0.05 in/in/min, the tensile specimens were tested at ambient temperature using a 1-inch-long extensometer.

Charpy impact tests were conducted per ASTM specification E23-66 (1) on longitudinal sections cut from 1/2-inch-thick plate. The specimens, with V-notch perpendicular to the rolled surfaces, were tested at temperatures from -30° to 150° C. All decarburized surfaces were removed from the plate before making into test specimens, and when heattreated the specimen V-notch was made afterwards.

Sections of both the 1/2- and 1/5-inch-thick steel plates in the as-rolled and heat-treated (600° C) conditions were examined for grain size (ASTM E112-63) (2) and for structure. The plate sections were mounted in Bakelite and ground and polished by standard procedures for visual and electron-microscopy examination. The specimens were etched with 5 vol-pct picral for visual examination and 2 vol-pct nital for electron microscopy studies. Chromium-shadowed carbon-plastic replicas were used for electron microscopy. For ferrite grain size, the intercept technique was used. Thin sections of selected steel plate in both the as-rolled and heat-treated (600° C) conditions were examined by transmission electron microscopy.

RESULTS AND DISCUSSION

Copper Precipitation Studies

Copper-precipitation treatments were studied first to determine the treatment to be used on tensile and impact-test specimens. Figure 1 shows the hardness of steels 115, 118, and 126, all containing about 1 wt-pct copper, and steel 120, containing 0.28 wt-pct copper, after heattreating at 500° and 600° C for up to 8 hours. As can be observed, maximum hardening occurred in 1-1/6 hours (70 minutes) to 4 hours at 500° C for the steel containing 1 wt-pct copper. This treatment time was considered too lengthy to be considered as a post-rolling treatment. Precipitation treatments were also conducted on steel 115 for up to 2 hours at 650° C. The time for optimum hardness was very short, up to about 5 to 10 minutes, but treatment at this temperature was also considered to be improper as the hardness increase was too small--about 5 Rockwell B hardness numbers--to justify the post-rolling treatment.

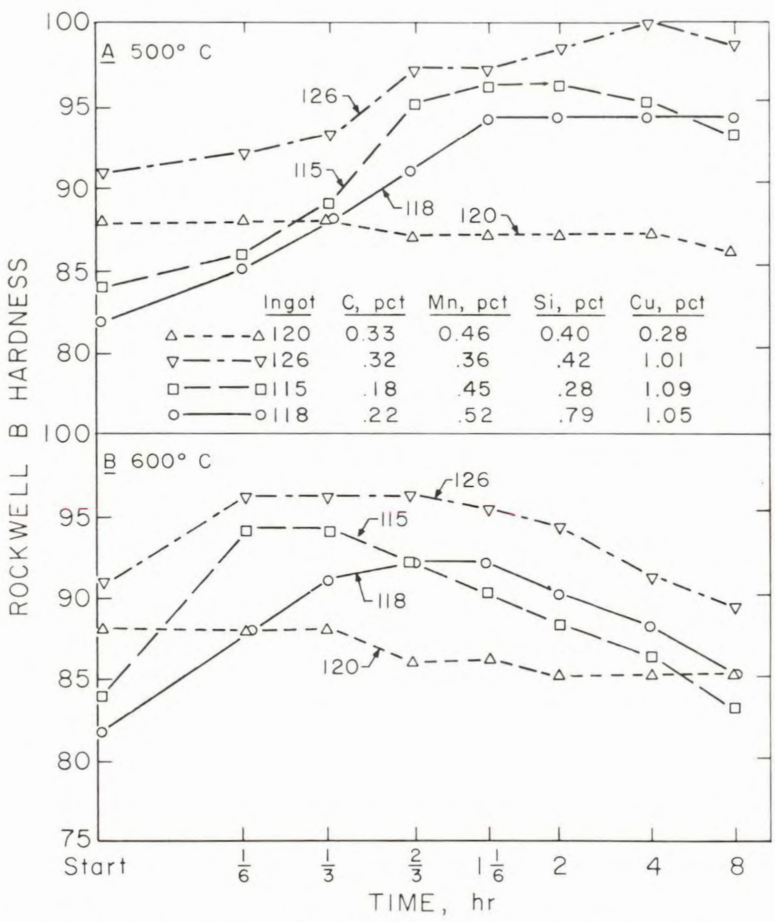

FIGURE 1. - Effect of *(A)* 500° and *(B)* 600° C heat treatments on Rockwell B hardness.

Although the maximum hardness attained by treatment at 600° C was slightly less than at 500° C, the time (1/6 to 1/3 hour, or 10 to 20 minutes) was considered to be satisfactory. All the steels for tensile and impact testing in the heat-treated condition were held at 600° C for 20 minutes, the time at which all of the steels reached maximum hardness.

Plots of the change in hardness of the steels in figure 1 are shown in figure 2. From the latter figure, the following are apparent:

1. Increasing silicon contents of steels (115 and 118) containing 0.2 wt-pct carbon and 1.0 wt-pct copper do not reduce hardening by copper precipitation. However, the time to reach equivalent hardness is increased at 600° C by increasing silicon contents. The delay in hardening, which is in agreement with previous findings (9), is probably caused by silicon reducing the diffusion rate of copper.

2. Increasing carbon contents of steels (115 and 126) containing 1 wt-pct copper considerably reduce hardening by copper. Because of the slight improvement of strength, post-rolling heat treatments would not be economical or beneficial for steel containing 0.3 wt-pct carbon. For this reason, most of the subsequent strengthening studies were conducted on steels containing 0.2 wt-pct carbon.

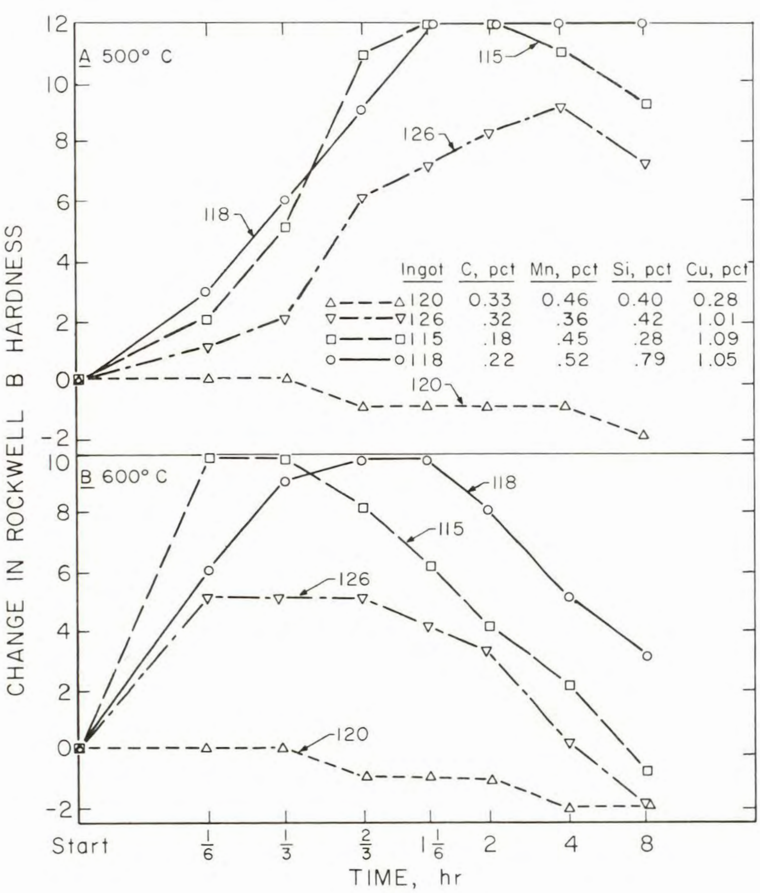

FIGURE 2. - Change in Rockwell B hardness from heat-treating at *(A)* 500° and *(B)* 600° C.

3. Softening of ferrite-pearlite structures (steel 120) occurred after 20 minutes.

Tensile Tests

The tensile test data for the 1/5-inch-thick plate in both the hot-rolled and heat-treated (600° C for 20 minutes) conditions are given in tables 3 and 4, respectively. The tensile and yield strength data are an average of the transverse and longitudinal tests (maximum variation of 1.6 Kpsi). The longitudinal strength was usually, but not always, greater. All of the steels had good ductility, as indicated by the elongation and reduction in area values. Ductility exceeded 17 percent elongation in both the heat-treated and hot-rolled conditions for 0.2-wt-pct carbon steel, and it was only slightly less for 0.3-wt-pct carbon steels. As is normal for hot-rolled carbon steels, the ductility becomes less with increasing strengths.

TABLE 3. - Tensile test data, hot-rolled condition

Series and target composition	Heat	Tensile strength, Kpsi	Yield strength, Kpsi	Elongation, pct	Reduction in area, pct
Series I: Varying Cu contents and 0.2 wt-pct C.	121	73.0	46.0	27	50
	112	75.0	52.0	28	55
	122	71.0	46.2	33	55
	113	80.4	56.3	26	54
	115	81.0	57.3	25	46
Series II: Varying Cu contents and 0.3 wt-pct C.	120	97.9	61.7	24	38
	123	89.0	56.3	20	33
	124	92.4	59.1	20	38
	125	95.0	60.1	21	36
	126	97.4	60.5	21	36
Series III: Varying Si contents, 0.2 wt-pct C, and 0.6 wt-pct Cu.	138	71.9	47.6	25	49
	137	76.2	51.9	26	48
	145	76.7	54.1	29	53
	141	85.0	57.3	24	39
	143	92.6	64.1	25	49
Series IV: Varying Si contents, 0.2 wt-pct C, and 0.8 wt-pct Cu.	146	76.1	52.3	23	41
	147	77.3	53.8	30	50
	148	87.4	61.6	28	48
	149	93.4	65.7	25	46
Series V: Varying Si contents, 0.2 wt-pct C, and 1.0 wt-pct Cu.	115	79.1	57.3	25	46
	119	80.1	54.2	26	46
	117	85.0	60.6	24	42
	118	91.5	64.7	28	45
	135	97.3	67.3	24	49

The tensile strengths for the 1/5-inch-thick steels in the hot-rolled condition are plotted in figure 3. Readily apparent are (1) the tendency for increase in strength with increasing carbon, copper, and silicon contents, and (2) the considerable scatter in strength data for any one series of steels. Because of the scatter, it is difficult to discriminate between the strengthening effects of copper and those of silicon.

TABLE 4. - Tensile test data, heat-treated condition

Series and target composition	Heat	Tensile strength, Kpsi	Yield strength, Kpsi	Elongation, pct	Reduction in area, pct
Series I: Varying Cu contents and 0.2 wt-pct C.	121	72.8	46.1	32	54
	112	76.2	51.3	28	53
	122	70.3	48.5	25	51
	113	83.7	57.9	24	52
	115	94.8	73.9	20	36
Series II: Varying Cu contents and 0.3 wt-pct C.	120	98.8	66.4	22	36
	123	89.7	59.0	17	25
	124	94.5	63.1	20	30
	125	97.7	67.2	23	35
	126	105.4	76.9	21	31
Series III: Varying Si contents, 0.2 wt-pct C, and 0.6 wt-pct Cu.	138	71.1	47.5	28	51
	137	71.0	50.3	28	49
	145	75.5	54.0	28	47
	141	85.6	58.9	20	38
	143	92.9	66.0	24	45
Series IV: Varying Si contents, 0.2 wt-pct C, and 0.8 wt-pct Cu.	146	76.9	54.4	28	46
	147	77.7	54.7	30	54
	148	89.8	61.7	26	48
	149	93.9	66.3	26	51
Series V: Varying Si contents, 0.2 wt-pct C, and 1.0 wt-pct Cu.	115	94.8	73.9	20	36
	119	92.5	67.3	18	45
	117	98.5	75.2	22	39
	118	105.9	79.8	22	44
	135	107.6	82.3	21	45

To avoid making a large number of steel heats to evaluate the strengthening effects of the additions, the decision was made to recalculate the strengths of each steel heat to certain standard definite compositions. The standard compositions to which strengths were recalculated are as follows:

	Element, wt-pct			
	C	Mn	Si	Cu
Series I..................	0.20	0.45	0.25	Variable.
Series II..................	.30	.45	.25	Variable.
Series III.................	.20	.45	Variable	0.60
Series IV..................	.20	.45	Variable	.80
Series V...................	.20	.45	Variable	1.00

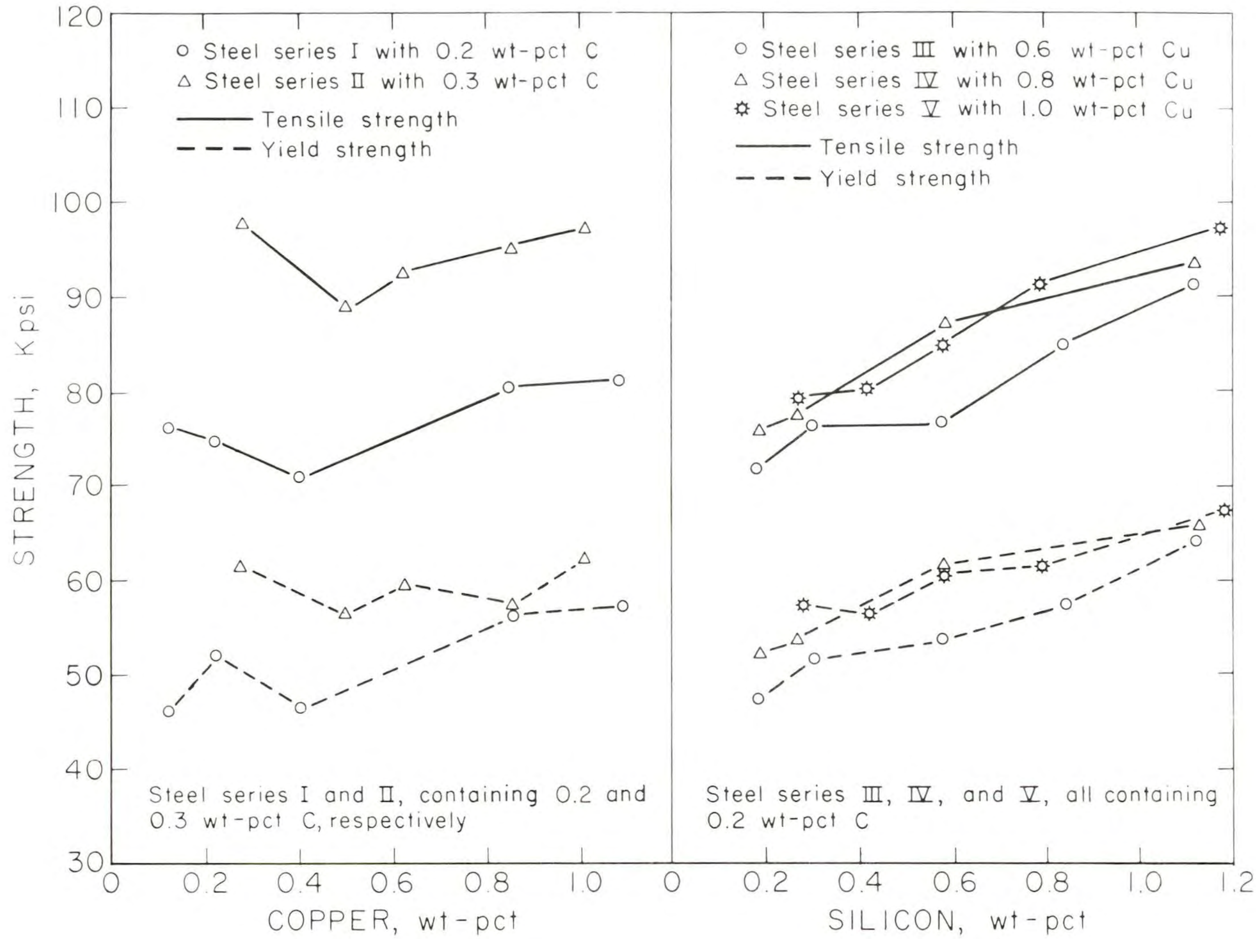

FIGURE 3. - Tensile and yield strengths of hot-rolled steels.

The strength data for carbon, manganese, and silicon (except when silicon is the variable) were modified by using the following equation (3), which is used to recalculate tensile strength of hot-rolled steel:

$$\text{Tensile strength (Kpsi)} = 38 \times [1 + (2.4 \times \text{wt-pct C})] \times [1 + (0.09 \times \text{wt-pct Mn})]$$
$$\times [1 + (1.50 \times \text{wt-pct P})] \times [1 + (0.40 \times \text{wt-pct Si})]$$
$$\times [1.07 + 0.22\,G + 1.00\,G^2)],$$

where G is the gage thickness of the steel in inches, taken as 0.2. Good agreement between the actual tensile test strengths and strengths calculated by use of this equation was obtained for hot-rolled steels with low copper contents. For example, the calculated strength of steel 121 was only 0.3 Kpsi higher than the test value. Although the equation was not intended for calculating yield strength, it was used for adjusting yield strengths, as they vary almost directly with tensile strength (12). Using the above equation, the following corrections were then calculated and applied for each 0.01-wt-pct composition variation in carbon, manganese, and silicon. Corrections were not applied for phosphorus, as its content (0.013 to 0.018 wt-pct) variation did not significantly change strength values.

Element	Correction, Kpsi
Carbon...........	1.10
Manganese........	.07
Silicon..........	.26

Figure 4 shows the corrected tensile and yield strength for series I and II steels, with varying copper contents, in both the hot-rolled and heat-treated conditions. As can be noted, the data points for each steel series are much more linear for the hot-rolled steel than are the corresponding data points in figure 3. The exceptions are those for the heat-treated steels containing 1 wt-pct or more copper. Linear equations were derived by least-squares analysis, and lines for these equations are given in the figure for each steel series in both conditions except for the steels with over 1 wt-pct copper.

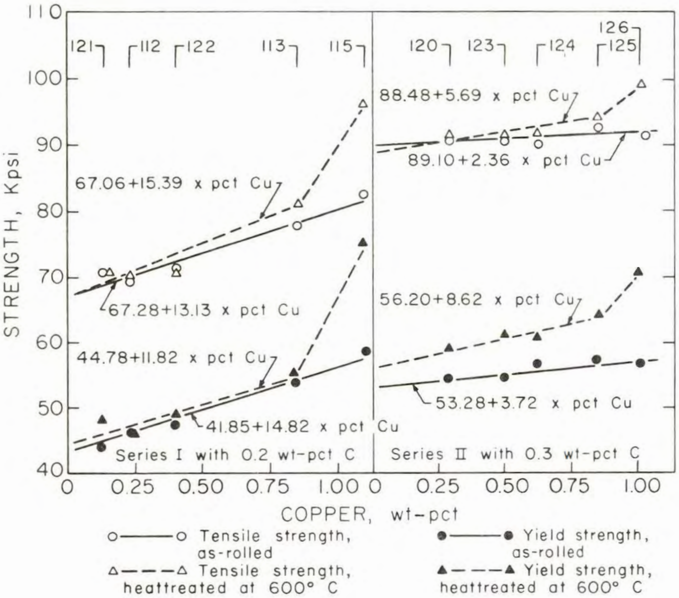

FIGURE 4. - Effect of copper on tensile properties of hot-rolled and heat-treated steels containing 0.2 or 0.3 wt-pct C, 0.45 wt-pct Mn, and 0.25 wt-pct Si. The strength data were modified to correct for composition variations, as discussed on pp. 10-11.

From the data points and strength equations the following conclusions were reached regarding strengthening by copper:

1. For hot-rolled steels, strengthening was greater for 0.2-wt-pct carbon steels than for 0.3-wt-pct carbon steels. The lower strengthening by copper in the 0.3-wt-pct carbon steels was believed to be due to segregation of copper in certain structural zones. In the dendrites of cast 0.3-wt-pct carbon steels, concentrations of copper were as much as 5.6 times greater in interdendritic pearlite regions than in the ferrite dendrite branches. These concentrates tended to persist in the rolled steels. Because the copper tended to concentrate, strengthening by copper would not be as large as when copper was uniformly distributed in the steel matrix. In contrast, little segregation was found in cast or rolled 0.2-wt-pct carbon steels.

2. The same effect was noted for the 0.2- and 0.3-wt-pct carbon steels containing up to about 0.85 wt-pct copper in the heat-treated condition.

3. Little increase in strength of the steels in the heat-treated condition over hot-rolled steels was found except for the yield strengths of series II steels containing 0.3 wt-pct carbon. The reason for the yield strength response was not known.

4. Significant increase in strengths occurred for heat-treated steels containing over 1 wt-pct copper. The increase was greater for steels containing 0.2 wt-pct carbon. The poorer response of the 0.3-wt-pct carbon steels, as mentioned previously, may be due to copper segregation.

The strength data for steel series III, IV, and V also were adjusted according to variations of carbon, manganese, and copper from the standard composition, but not for silicon as it was the variable. These steel series contained nominal contents of 0.6, 0.8, and 1.0 wt-pct copper, respectively, along with 0.2 wt-pct carbon and 0.45 wt-pct manganese. For copper corrections, the slope of the tensile strength line for the hot-rolled steel of series I steels was used; that is, a correction of 0.13 Kpsi was applied for each 0.01-wt-pct deviation from 0.60, 0.80, or 1.00 wt-pct copper. The same corrections for carbon and manganese were used as for series I and II steels.

The corrected tensile and yield strengths of steel series III, IV, and V in both the hot-rolled and heat-treated conditions are illustrated in figure 5.

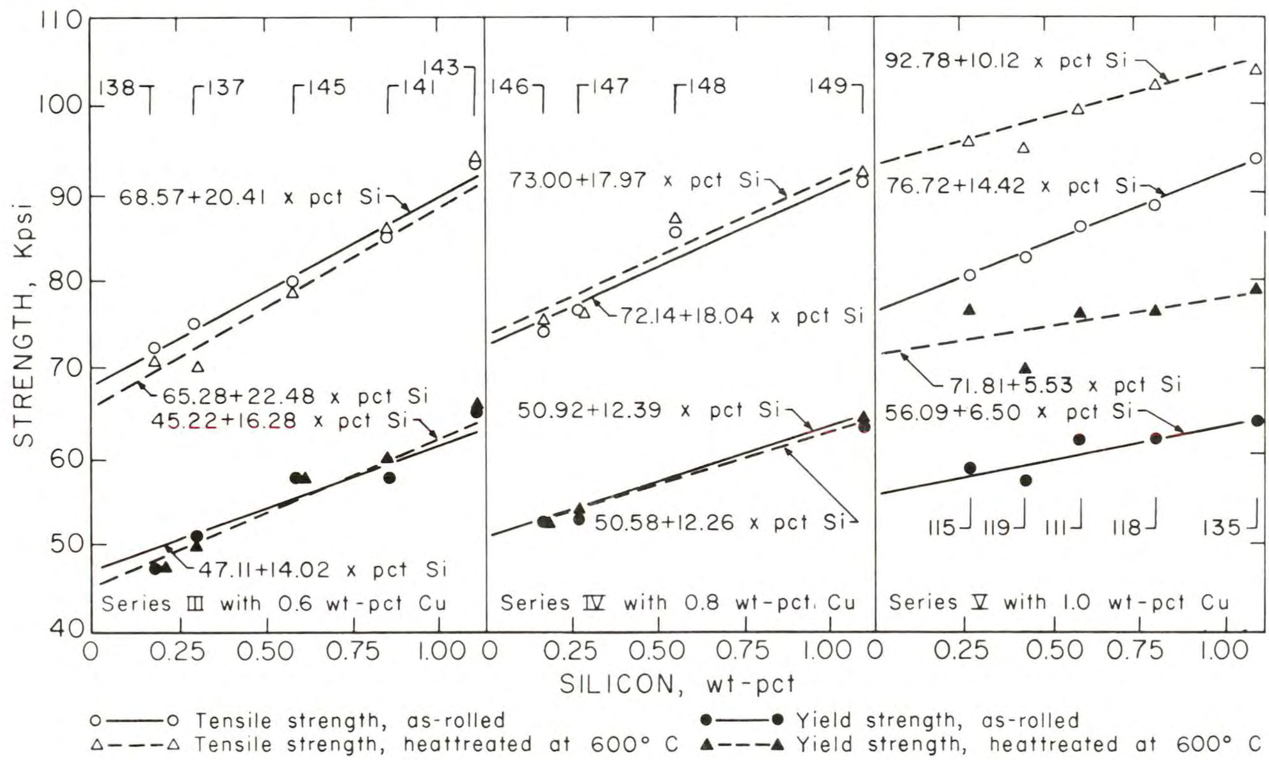

FIGURE 5. - Effect of silicon on tensile properties of hot-rolled and heat-treated steels containing 0.2 wt-pct C, 0.45 wt-pct Mn, and 0.60, 0.80, or 1.00 wt-pct Cu. The strength data were modified to correct for composition variations, as discussed on pp. 12-13.

From the linear equations and the data points, the following conclusions were reached for the effect of copper on the strength of silicon steels.

1. Copper has an adverse effect on strengthening by silicon. As the copper content increases from 0.6 to 1.0 wt-pct, the rate of increase in strengthening by silicon becomes smaller. The reason was not established, but there apparently is an interrelated effect between silicon and copper.

2. For steels containing 0.6 and 0.8 wt-pct copper, there is no significant change in the strengths after heattreating. Lack of strengthening by copper precipitation at these copper contents is in agreement with previous findings (13).

3. A significant increase in strength by copper precipitation occurs in heat-treated steels containing more than 1 wt-pct copper. The slope of the strength equations for the steels containing 1 wt-pct copper in the heat-treated condition is less than for the hot-rolled steels. As indicated by the hardness data in figures 1 and 2, the strengths for the steels with larger silicon contents may have been greater if longer heat treatments were used.

Impact Tests

The effect of copper and silicon on the Charpy impact strength at room temperature of the steel in the hot-rolled and heat-treated conditions is illustrated in figure 6. From the data, the following observations can be made:

1. Increasing copper contents increased the impact strength of steels containing nominal contents of 0.2 wt-pct carbon and 0.2 wt-pct silicon (steel series I), in both hot-rolled and heat-treated conditions. The exception was the steel containing over 0.85 wt-pct copper in the precipitation-strengthened condition, which was drastically lower in impact strength. The increase in impact strength by increasing copper contents was previously reported (12). The increase is believed to be due to the increase in hardenability by copper.

2. In contrast to observation 1, increasing copper contents in steels containing 0.3 wt-pct carbon (steel series II) resulted in little change in impact strength, which was relatively low at all copper contents. This would indicate that carbon has a predominant effect over copper on the impact strength of hot-rolled steels.

3. Silicon contents of up to about 0.3 wt-pct improved the impact strength of 0.2-wt-pct carbon steels containing 0.6 and 0.8 wt-pct copper (steel series III and IV). This also may be true for steels containing 1.0 wt-pct copper (steel series V) with less than 0.3 wt-pct silicon, but they were not studied.

4. Silicon contents over 0.3 wt-pct decreased the impact strength of 0.2-wt-pct carbon steel containing 0.6, 0.8, and 1.0 wt-pct copper in the

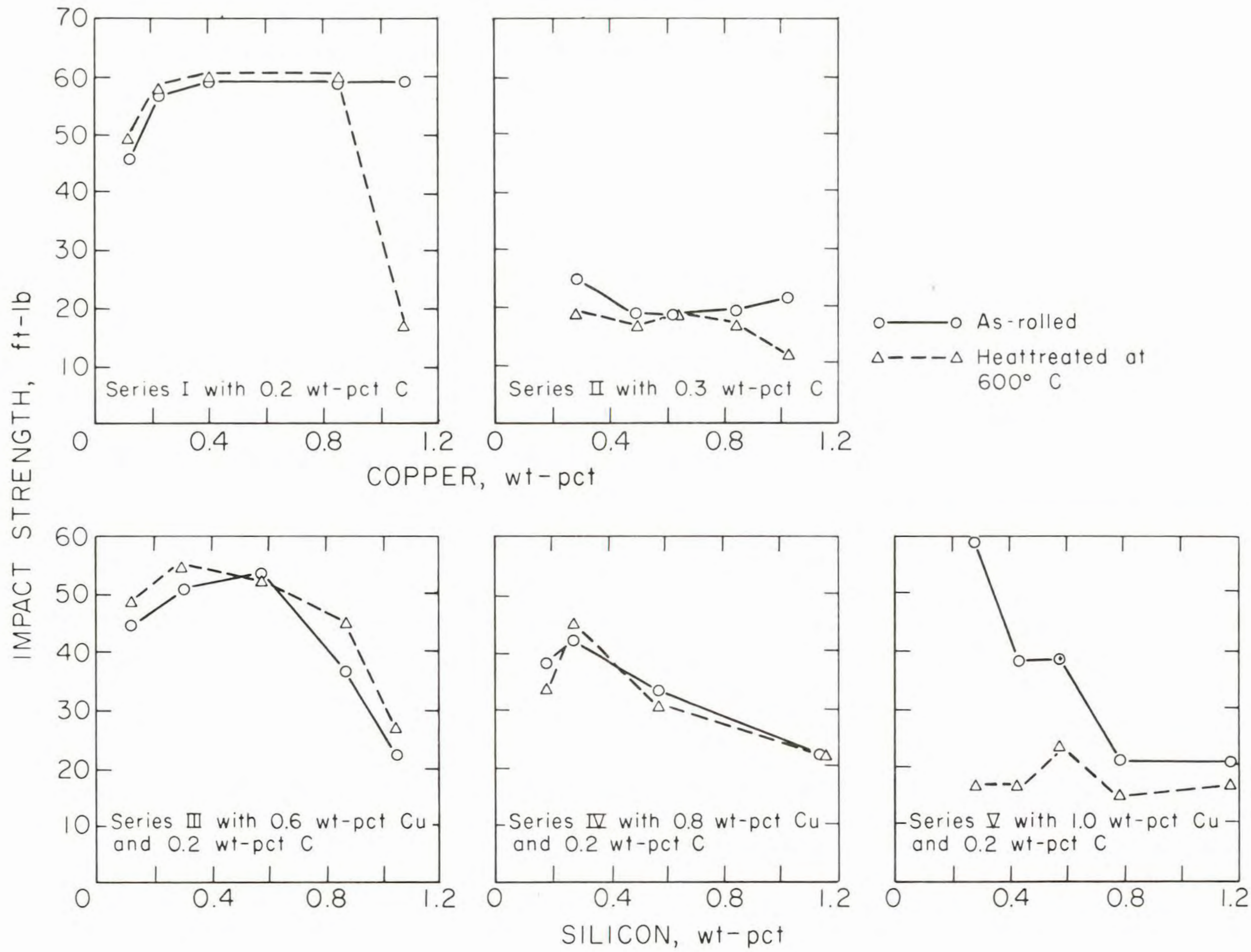

FIGURE 6. - Effect of copper and silicon on impact strength of steels of series I, II, III, IV, and V.

hot-rolled condition. When heattreated, the silicon content did not significantly change the hot-rolled impact strength except for those steels containing over 0.85 wt-pct copper. The low impact strengths of such steels in the heat-treated condition were similar to the steels containing 0.3 wt-pct carbon (steel series II). The increase in impact strength with up to 0.3 wt-pct silicon and then a decrease with further silicon contents is in agreement with Frazier and coworkers (6) for steels without copper additions.

The effect of copper and silicon on the ductile-brittle transition temperature of a few select steels containing 0.2 wt-pct carbon in the hot-rolled condition is shown in figure 7. Except for steel 118 (containing high copper and silicon contents) the transition temperature from completely ductile to partially brittle (cleavage) fracture occurred between 20° and 50° C. Increasing copper and silicon contents tended to lower the impact strength and percent of ductile fracture (in the ductile-brittle transition temperature range). At 0° C, the ductility of all the steels was about the same, 20 percent ductile fracture. Steels (118) containing about 0.8 wt-pct silicon and 1.0 wt-pct copper had an especially high transition temperature

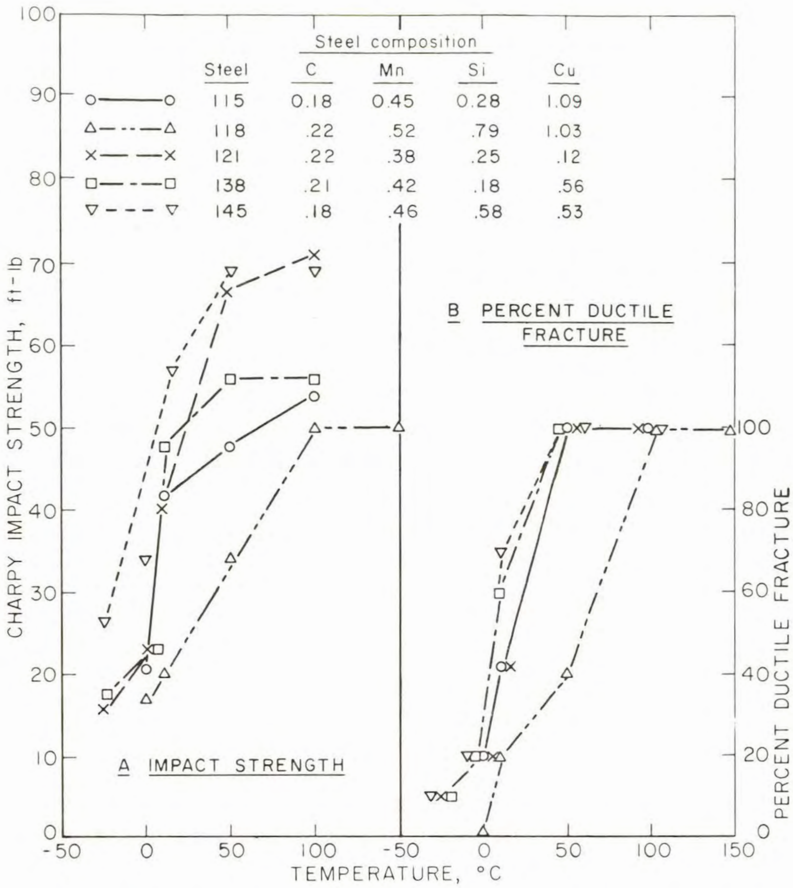

FIGURE 7. - *(A)* Charpy impact strength and *(B)* percent ductile fracture of select steels over a range of temperatures.

in the hot-rolled condition, which probably would be much worse when heattreated.

Because of low impact strengths observed for steels with high silicon contents, the silicon content of 0.2-wt-pct carbon steels containing copper should be held to the minimum level necessary to prevent hot-shortness by copper. Using a 30 ft-lb impact strength as the lowest acceptable value, it was determined that a 0.6-wt-pct copper steel should contain no more than about 0.8 wt-pct silicon, and a 0.8-wt-pct copper steel no more than about 0.6 wt-pct silicon. Because of the deleterious effect of precipitation heat treatments on the impact strength of 0.2-wt-pct carbon steels containing over 0.85 wt-pct copper, they probably should not be considered at all for hot-rolled steels of these contents. Even though the steels may not be given a post-rolling heat treatment, when welding and torch cutting is done, a heat-treated zone will occur. Of course the detrimental nature of the heated zone depends upon its relationship to stress in the fabricated steel part. A normalizing treatment could be used to eliminate the embrittling effect of copper precipitates, as copper precipitation does not occur with this type of treatment (13).

Microstructures

The structures of all the hot-rolled and heat-treated steels were examined. The ferrite grain size of all the steels was ASTM 9.5 to 10.5 (2). These fine grain sizes are typical for steels normalized by heattreating immediately above the gamma iron-gamma iron plus alpha iron solvus and then air-cooling. The grain size and pearlite colonies tended to become smaller with increasing copper and silicon contents. Because finer grains and pearlite colonies contribute to strengthening (5), not all the increase in strength observed can be attributed to copper solutes or precipitates or silicon solutes. Typical examples of the effect of increasing copper and silicon contents on structure are observed in figures 8 and 9. The structure

FIGURE 8. - Structure of steel 146 containing 0.2 wt-pct C, 0.8 wt-pct Cu, and 0.19 wt-pct Si. (X 1,000)

FIGURE 9. - Finer structure of steel 149 containing 0.2 wt-pct C and 0.8 wt-pct Cu, but with 1.13 wt-pct Si. (X 1,000)

observed in the steel (149) containing 1.13 wt-pct silicon is finer than the steel (146) containing 0.19 wt-pct silicon. Both steels also contained 0.2 wt-pct carbon and 0.8 wt-pct copper.

No copper precipitates were observed by transmission electron microscopy in the hot-rolled steels or in the heat-treated steels containing less than 0.85 wt-pct copper. A typical example of hot-rolled steels without copper precipitates is illustrated in figure 10, obtained by thin-section electron microscopy. Copper precipitates observed on heattreating (600° C) steels containing greater copper than 0.85 wt-pct copper are illustrated in figure 11. As can be observed, copper precipitates formed largely within the alpha iron lattice, which is in agreement with Hornbogen's findings (11). Unexplained was the uniform distribution of copper precipitates in the heat-treated condition of 0.3-wt-pct carbon steels: Microprobe analysis had indicated a tendency for copper concentration near pearlite colonies at prior austenite grain boundaries in the hot-rolled condition.

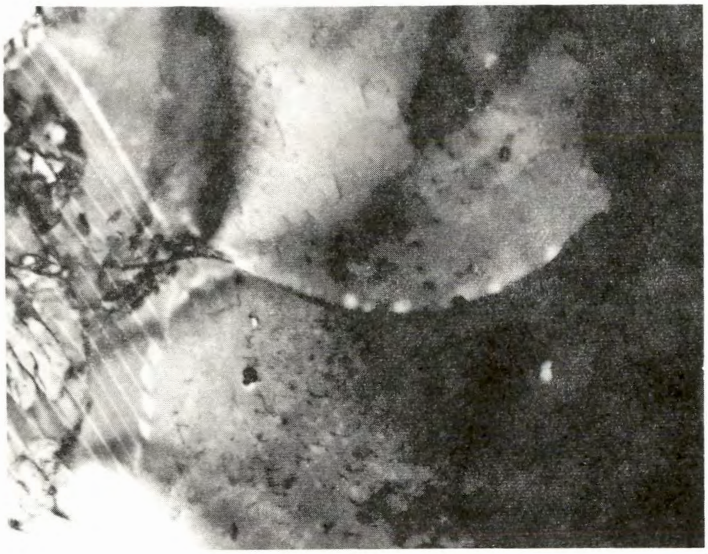

FIGURE 10. - Absence of copper in hot-rolled steel 118 containing 1.05 wt-pct Cu. (X 50,000)

FIGURE 11. - Copper precipitates in steel 118 after heattreating at 600° C. (X 50,000)

SUMMARY

The effects of copper and silicon contents of up to 1 wt-pct on selected mechanical properties of steels containing 0.2 wt-pct carbon, and the effect of copper on 0.3-wt-pct carbon steels were studied. The steels were prepared by induction melting, forging, and rolling to 1/2- and 1/5-inch plate. The steel plates were evaluated by conducting copper precipitation heat treatments; hardness, tensile, and Charpy impact tests; and metallographic studies.

Hardness data were taken to record the effect of copper precipitation treatments at 500°, 600°, and 650° C. The higher carbon and silicon contents were found to delay the time at which maximum strengthening was attained. Although the maximum hardness attained at 600° C was slightly less than that obtained at 500° C, a heat treatment at 600° C was considered better for use as a post-rolling treatment than at 500° or 650° C.

Copper and silicon were both found to be effective strengtheners of steel. In steels containing about 0.25 wt-pct silicon and 0.2 or 0.3 wt-pct carbon, a linear relationship between strength and copper content was found in the hot-rolled condition. Strength increases attained by copper additions to 0.3-wt-pct carbon steels were less than those for 0.2-wt-pct carbon steels. A slight increase in strength occurred in steels containing up to 0.85 wt-pct copper on heattreating at 600° C, but no decided strengthening by copper precipitation was found until greater amounts of copper were present. An interaction between copper and silicon concerning strength was observed in steels containing 0.2 wt-pct carbon. The reason for the interaction was not apparent, but it was observed that the greater the copper content of the steel the less the strengthening by silicon in both the hot-rolled and heat-treated conditions. The occurrence of an interaction in 0.3-wt-pct carbon steels was not studied. Copper and silicon additions refined the grain size to a small extent, which would add to strengthening by copper, silicon, and carbon.

The effect of copper and silicon on the impact strengths was dependent upon their content as well as on the steel condition. The impact strength of as-rolled, 0.2-wt-pct carbon steels containing 0.25 wt-pct silicon increased with increasing copper contents. The same behavior was noted after heating the steels at 600° C until over 0.85 wt-pct copper was present, when a drastic lowering occurred. A maximum in impact strength occurred at about 0.3 wt-pct silicon in steels containing 0.2 wt-pct carbon and 0.6, 0.8, and 1.0 wt-pct copper. At larger silicon contents, the greater the copper content the lower the impact strength. Steels with high silicon and copper contents had a high ductile-brittle transition temperature in the hot-rolled condition. Low impact strengths were recorded for all 0.3-wt-pct carbon steels in both conditions.

The extent to which silicon additions can be used to prevent surface hot-shortness by copper appears to be limited. Using 30 ft-lb of absorbed energy as a minimum impact energy, silicon contents should be limited to a maximum of 0.8 wt-pct for 0.6-wt-pct copper steels and 0.6 wt-pct for 0.8-wt-pct-copper steels containing 0.2 wt-pct carbon. For steels of the same carbon content and over 0.85 wt-pct copper, 0.6 wt-pct silicon is maximum in the hot-rolled condition. Steels of these latter copper and carbon contents should not be considered for notch-sensitive applications when post-rolling heat treatments (copper precipitation) or welding are involved. Steels containing 0.3 wt-pct carbon do not respond significantly to strengthening by copper precipitation and they have low impact strength; for example, below 30 ft-lb at all copper contents and conditions.

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