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Effect of Copper and Tin on Mechanical Properties of Hot-Rolled 0.2 Wt-Pct Carbon Steels

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By Mark I. Copeland, John S. Howe, and James C. Sarvis
Albany Metallurgy Research Center, Albany, Oreg.

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Thomas V. Falkie, Director

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EFFECT OF COPPER AND TIN ON MECHANICAL PROPERTIES OF HOT-ROLLED 0.2 WT-PCT CARBON STEELS

by

Mark I. Copeland,[1] John S. Howe,[2] and James C. Sarvis[2]

ABSTRACT

Bureau of Mines researchers investigated the combined effect of copper and tin additions on the mechanical properties of hot-rolled steels. Wrought steels containing 0.2 wt-pct C and up to 0.2 and 1.0 wt-pct Sn and Cu, respectively, were made and evaluated by conducting tensile and impact tests and electron-beam microprobe and electron microscopy examination. Tin additions did not significantly affect the tensile properties of steel at different copper contents in the hot-rolled condition. Tin lowered the copper content at which strengthening by copper precipitation normally starts, 0.8 wt-pct, and decreased the strength of steel aged at 1,022° F (550° C). The most adverse effect of tin was lowering the notch toughness of steels at most copper contents.

INTRODUCTION

Increasing copper and tin contents of ferrous scrap and increasing ecological and economical pressures to utilize ferrous scrap containing these elements are a growing problem for the steel industry. Automotive scrap and municipal waste (tin cans), which usually contain much less than 1 wt-pct Cu and 0.2 wt-pct Sn, are of special commercial importance. The recovery and recycling of ferrous scrap containing these residual elements have been extensively explored. However, the metallurgical implications of the residuals have not been as extensively explored. Copper and tin are of concern because these elements are difficult to remove (13)[3] during the steelmaking process.

Many investigators have studied the phases in steels containing copper or tin and the effect of these elements on the tensile properties and hardness values of various types of steels. Tin, which is soluble in pure iron up to about 10 wt-pct at low temperatures (9), does not form an iron-tin intermediate phase (10) in plain carbon steels containing up to 0.5 wt-pct

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[1] Metallurgist.
[2] Physical science technician.
[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

Sn, and it does not form carbides or nitrides (17). Copper, whose solubility in iron (10) is much less than tin, also does not form nitrides or carbides. Numerous investigators agreed that tin (7, 10, 16) and copper (6, 12) increase the strength and hardness and reduce the ductility of steel. Steels containing more than about 0.8 wt-pct Cu may be strengthened by application of copper-precipitation heat treatments (6). However, steels containing less than about 1.0 wt-pct Sn cannot be similarily enhanced because of the extensive solubility of tin in iron.

Tin or copper may influence the toughness of steel. Early investigators (7, 20) agreed that increasing tin contents lowered the energies absorbed during room temperature rupture testing of Izod and Charpy impact specimens. More recently, Shelmerdine (16) observed that tin caused a progressive increase in the ductile-brittle transition temperature and a decrease of the ductile strength of Charpy impact specimens (made from normalized, low-carbon steel). These changes were not significant until the tin content exceeded 0.4 wt-pct. Thwaites (19) concluded that the decreasing ductile strength and increasing intergranular embrittlement of steel with increasing tin contents were caused by segregation of tin at the grain boundaries. In contrast to tin, increasing copper contents can improve the notched impact properties of hot-worked or normalized steels (4, 11). Copper-precipitation heat treatments of hot-worked steels containing greater than 0.8 wt-pct Cu reduce the impact strength.

In the present work, the effect of combinations of copper and tin on selected mechanical properties of 0.2 wt-pct carbon steels was studied. Steel plates were made by induction melting, forging, and rolling. The steels were evaluated by conducting tensile, impact, metallographic, and electron-beam microprobe tests.

PROCEDURE

Four series of 0.20 wt-pct C were made to determine the effect of up to about 1.0 wt-pct Cu on the mechanical properties of steels containing 0, 0.5, 0.10, and 0.20 wt-pct Sn. The target composition for each steel series is given in table 1, and the actual chemical analyses are listed in table 2. In addition to the listed contents, the steels contained 0.13 to 0.15 Ni, 0.008 to 0.010 P, 0.024 to 0.032 S, all in weight-percent. The silicon content of the steels was maintained at 0.25 to 0.40 wt-pct for two reasons: The impact toughness of steels containing copper and 0.2 wt-pct C was previously found to be optimum at these silicon contents (4), and larger silicon contents than normally used (<0.2 wt-pct) are beneficial in preventing surface hot shortness by molten copper (5). Carbon contents of 0.2 wt-pct, rather than 0.3 wt-pct were used, as the author found previously (4) that the notch toughness of wrought steels containing 0.3 wt-pct C, which were <20 ft-lb, was not significantly changed by increasing copper contents. By a similar analogy, the notch toughness of wrought, 0.3 wt-pct carbon steels, may not be significantly changed by tin additions. The manganese additions employed, 0.50 to 0.80 wt-pct, are typical contents used for commercial 0.2 wt-pct carbon steels with fair toughness.

TABLE 1. - Target composition of steel heats

Series	Content, wt-pct				
	C	Mn	Si	Cu	Sn
1..........	0.18-0.23	0.55-0.80	0.25-0.40	Up to 1.0	0
2..........					0.04-0.06
3..........					.08- .12
4..........					.18- .22

TABLE 2. - Chemical analysis of steel heats

Series number and nominal content	Heat	Content, wt-pct				
		C	Mn	Si	Cu	Sn
1--with no Sn and up to 1.0 wt-pct Cu.	1	0.20	0.52	0.40	0.23	Nil
	2	.20	.55	.32	.44	Nil
	3	.23	.75	.28	.58	Nil
	4	.21	.68	.36	.93	Nil
	5	.20	.61	.27	1.05	Nil
2--with 0.05 wt-pct Sn and up to 1.0 wt-pct Cu.	6	.23	.71	.39	.03	0.05
	7	.21	.72	.26	.26	.05
	8	.21	.71	.34	.43	.05
	9	.22	.75	.36	.62	.05
	10	.22	.73	.37	.81	.05
3--with 0.10 wt-pct Sn and up to 1.0 wt-pct Cu.	11	.21	.59	.37	.25	.12
	12	.22	.66	.40	.42	.12
	13	.20	.57	.39	.65	.12
	14	.22	.66	.33	.80	.10
	15	.22	.64	.33	.98	.10
4--with 0.20 wt-pct Sn and up to 1.0 wt-pct Cu.	16	.22	.73	.40	.20	.19
	17	.20	.57	.38	.38	.21
	18	.22	.62	.34	.57	.21
	19	.20	.70	.41	.83	.19
	20	.22	.66	.33	.95	.19

The 20 steel heats, each weighing about 70 lb, were made by induction melting of SAE 1021 bar stock and by hot forging and rolling of 4-in-sq ingots. The bar stock contained 0.20 C, 0.80 Mn, 0.08 Cu, 0.15 Ni, all in weight-percent, and no detectable tin (<0.01 wt-pct). The melting, forging, and rolling procedures used were previously described (4). Steel plates measuring 1/2 and 1/5 inch thick were made for conducting the impact and tensile tests, respectively. The finish rolling temperature of each size plate was about 1,560° F (850° C). The steel plates were descaled by sand-blasting, and suitable size sections were removed at locations closely coinciding midway between the top and bottom of the ingots. The specimens were selected from this location to reduce any composition effect due to longitudinal segregation in the ingot.

Copper-precipitation aging treatments were conducted to determine the effect of tin on the hardening response of steels containing 1 wt-pct copper and to determine the temperature and time to process tensile and impact specimens to the optimum hardness. Sections of the hot-rolled plates were heated, and then Rockwell B hardness measurements were made on sanded sections.

The tensile tests were conducted on specimens made from 1-inch-wide by 5-inch-long sections cut from the 1/5-inch-thick plates. For both the hot-rolled and aged conditions, two specimens were made with the major dimension parallel to the rolling direction (longitudinal) and two transversely. Aging treatments, at 1,022° F (550° C) for 20 min, were performed before making the sections into tensile specimens. Ten minutes were allowed to heat the specimens to temperature, as determined by a thermocouple spotwelded to the specimen, before timing of the 20-min aging treatment was started. The gage section of the tensile specimen was 2-3/4 inches long and 0.250±0.005 inch wide. The tensile specimens were tested at room temperature at a strain rate of 0.05 in/in/min using a 1-inch extensometer.

Standard ASTM V-notched, Charpy impact specimens (1) were made from the 1/2-inch plate of all the steels, both in the hot-rolled and aged (550° C for 20 min) conditions. The specimens were made with their major length parallel to the rolling direction and with their notch perpendicular to the rolled surface. A minimum of two specimens was tested at room temperature on each steel in both conditions. Three additional specimens from selected steels were tested over a range of temperatures, ranging from -2° to 76° C, to determine the effect of temperature on the energy absorbed and to ascertain the ductile-brittle transition temperature (DBTT). The DBTT was judged to occur at the highest temperatures at which 100-pct ductile fractures were obtained with increasing test temperatures, when the tests were concluded.

Impact tests also were made over a range of temperatures on V-notched, Charpy specimens made from steel that had been given post-rolling normalizing heat treatments at 1,652°, 1,832°, and 2,012° F (900°, 1,000°, and 1,100° C, respectively) for 8, 4, and 1/2 hr, respectively. The purpose was to determine if the notch toughness of the steels could be improved. Normalizing treatments are frequently used because of the difficulty of controlling hot-rolling finish temperatures. Before normalizing the Charpy-specimen sections, 1/2-inch cubes were held for various times at the normalizing temperatures, water quenched, metallographically prepared, etched to reveal the austenite grain boundaries, and then the grain sizes were measured. The time to austenitize the Charpy specimen sections was determined by the minimum time to obtain ASTM 5-7 austenite grain sizes (2).

Sections of the 1/5- and 1/2-inch plates in the hot-rolled and aged (550° C for 20 min) conditions were examined for grain size, structures, and segregation. Sections were mounted and ground and polished by standard procedures. Diamond abrasives were used to polish. The mounts were etched with modified Vilella's etchants to reveal austenite and ferrite grain sizes and other structural features. Grain sizes were determined by the intercept technique (2). Selected metallographically prepared steels were examined for tin segregation with an electron-beam microprobe. Plastic-carbon replicas from the fractures of several broken Charpy specimens were examined by electron microscopy to determine the mode of fracture. Thin sections of selected steels also were examined by transmission electron microscopy for structural details.

RESULTS AND DISCUSSION

Aging Treatments

The effect of tin on hardening by copper precipitation was evaluated by aging three, hot-rolled, 1 wt-pct copper steels, numbers 5, 15, and 20 (table 2) containing zero, 0.1, and 0.2 wt-pct Sn, respectively. The steels were aged at 932°, 1,022°, and 1,112° F (500°, 550°, and 600° C, respectively). By the hardness curves in figure 1, the following was surmized:

1. Increasing tin contents lowered the maximum hardening response change. The change increased with rising temperatures.

2. The hardening response was most rapid and attained maximum response in shortest time at 1,022° F (550° C).

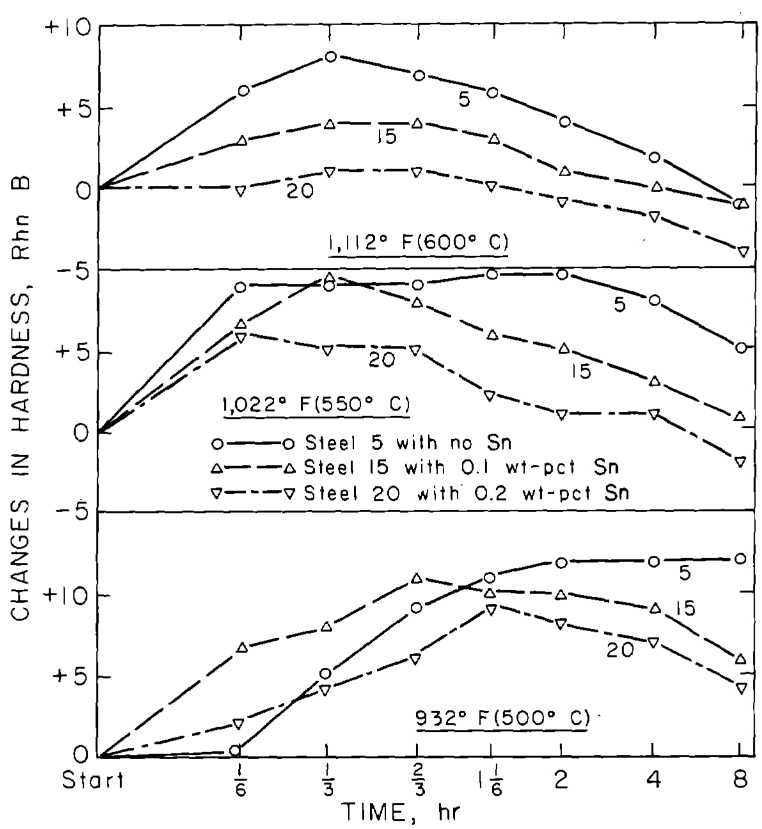

FIGURE 1. - Effect of aging temperature on hardness of 1 wt-pct Cu steels.

3. Tin decreased the hardening response time at 932° F (500° C) but it was not apparent at other temperatures.

From the hardening response curves (fig. 1) the decision was made to age harden all the tensile and impact specimens at 1,022° F (550° C) for 20 min. The response time at this temperature was much shorter, and the hardnesses produced were not significantly lower than at 932° F (500° C) but greater than at 1,112° F (600° C).

Tensile Properties

The tensile test data for the 1/5-inch-thick steel plates in the hot-rolled and aged, 1,022° F (550° C) for 20 min, conditions are given in tables A-1 and A-2, respectively, in appendix A. The strengths of the hot-rolled steels tended to be greater in the longitudinal direction and of the aged steels greater in the transverse direction. The average deviation in strength between the longitudinal and transverse directions was 1.8 kpsi for series 1-4, and the maximum deviation was 6.2 kpsi (steel 12 in aged condition). All the steels had good ductility. The elongations and reductions in area all exceeded 20 and 44 pct, respectively.

To compensate for unavoidable variations in C, Mn, and Si, and to permit direct comparison of heat-to-heat, the average yield and tensile strengths of the steels of series 1, 2, 3, and 4 were recalculated to a standard composition of 0.20 wt-pct C, 0.65 wt-pct Mn, and 0.25 wt-pct Si. The tensile and yield strength changes resulting from a 0.01 wt-pct variation in C, Mn, and Si contents were determined by use of an equation (3) intended for calculating tensile strength. The yield strength changes calculated for incremental composition variations by use of this equation, which follows, are only an approximation. However, the yield strengths do vary proportionally with the tensile strength (10).

$$\text{Strength (kpsi)} = 38\,[1 + (2.4 \times \text{wt-pct C})] \times [1 + (0.09 \times \text{wt-pct Mn})] \times [1 + (0.4 \times \text{wt-pct Si})] \times [1.07 + 0.22G + 0.1G^2]$$

where G is the steel thickness, 0.20 inch.

By inserting 0.20 wt-pct C, 0.65 wt-pct Mn, and 0.35 wt-pct Si in the equation and then varying each content 0.01 wt-pct, one at a time, the following strength changes were calculated for each 0.01 wt-pct variation.

C = 1.23 kpsi

Mn = 0.07 kpsi

Si = 0.27 kpsi

The strength changes resulting in correcting the compositions to 0.20 wt-pct C, 0.65 wt-pct Mn, and 0.35 wt-pct Si were then calculated. Corrections were not applied for phosphorus as its content variation would not significantly change strength values. The corrected strength values are given in table 3.

The corrected tensile and yield strengths for series 1, 2, 3, and 4 steels are plotted in figure 2. Linear equations, derived by least square analysis, and lines for the equations are given in the figure for the tensile and yield strengths of all the steels in the rolled condition and the steels of series 1, 2, and 3 in the aged condition at low copper contents where strengthening by copper precipitation is not significant. The strength lines of the aged steels at other contents were drawn to best fit the data except series 1 and 2 steels containing over 0.8 wt-pct Cu. The strength lines at these latter contents were drawn to intersect the strength lines of steels at 0.8 wt-pct copper, a content at which copper-precipitation strengthening was previously found (4) to start in steels containing no tin.

TABLE 3. - Compositions and recalculated strengths for series 1 to 4 steels

Steel	Composition, wt-pct			Correction for each content				Corrected strength, kpsi			
								Hot-rolled		Aged	
	C	Mn	Si	C	Mn	Si	Total Δ	Yield	Tensile	Yield	Tensile
SERIES 1											
1.......	0.20	0.52	0.40	0.0	+0.91	-1.35	-0.44	47.9	70.9	48.1	70.6
2.......	.20	.55	.32	.0	+.70	+.81	+1.51	49.3	71.5	47.4	71.5
3.......	.23	.75	.28	-3.70	-.70	+1.89	-2.51	50.2	72.9	48.1	73.9
4.......	.21	.68	.36	-1.23	-.21	-.27	-1.71	52.1	77.3	64.3	91.6
5.......	.20	.61	.27	.0	+.28	+2.16	+2.44	58.1	81.5	75.0	97.9
SERIES 2											
6.......	0.23	0.71	0.39	-3.70	-0.42	-1.08	-5.20	47.2	81.7	41.6	72.3
7.......	.21	.72	.26	-1.23	-.49	+2.43	-.71	49.7	75.2	48.7	76.2
8.......	.21	.71	.34	-1.23	-.42	+.27	-1.38	49.4	75.5	49.8	75.9
9.......	.22	.75	.36	-2.46	-.70	-.27	-3.43	50.1	75.7	49.6	75.8
10.......	.22	.73	.37	-2.46	-.56	-.54	-3.56	51.7	77.1	54.5	78.8
SERIES 3											
11.......	0.21	0.59	0.37	-1.23	+0.42	-0.54	-1.35	46.4	71.7	43.7	68.4
12.......	.22	.66	.40	-2.46	-.07	-1.35	-3.88	48.7	74.0	46.7	70.8
13.......	.20	.57	.39	.0	+.56	-1.08	-.52	52.4	77.2	52.9	78.0
14.......	.22	.66	.33	-2.46	-.07	+.54	-1.99	52.7	78.2	60.8	83.7
15.......	.22	.64	.33	-2.46	+.07	+.54	-1.85	55.5	77.7	68.4	87.6
SERIES 4											
16.......	0.22	0.73	0.40	-2.46	-0.56	-1.35	-4.37	49.3	73.6	45.9	71.0
17.......	.20	.57	.38	.0	+.56	-.81	-.25	49.8	73.2	48.9	73.5
18.......	.22	.62	.34	-2.46	+.21	+.27	-1.98	51.9	76.8	50.8	77.4
19.......	.20	.70	.41	.0	-.35	-1.62	-1.97	54.5	76.4	62.2	82.2
20.......	.22	.66	.33	-2.46	-.07	+.54	-1.99	55.5	79.5	66.5	86.4

The strength data in figure 2 indicate that tin has some rather unexpected effects, summarized as follows, on the strength of copper-bearing steels.

Hot-Rolled Condition

1. At low copper contents, the strengths of series 2 steels containing 0.05 wt-pct Sn are greater than the steels containing no tin or 0.1 and 0.2 wt-pct Sn. This effect should be restudied.

2. The strengths of the steels with the higher copper contents were similar at all tin contents, except for the yield strength of series 2 steels, which indicated that increasing copper contents tend to nullify the strengthening effect of tin.

Aged Condition

1. Increasing tin contents promote the development of lower strengths at copper contents below where strengthening by copper precipitation starts.

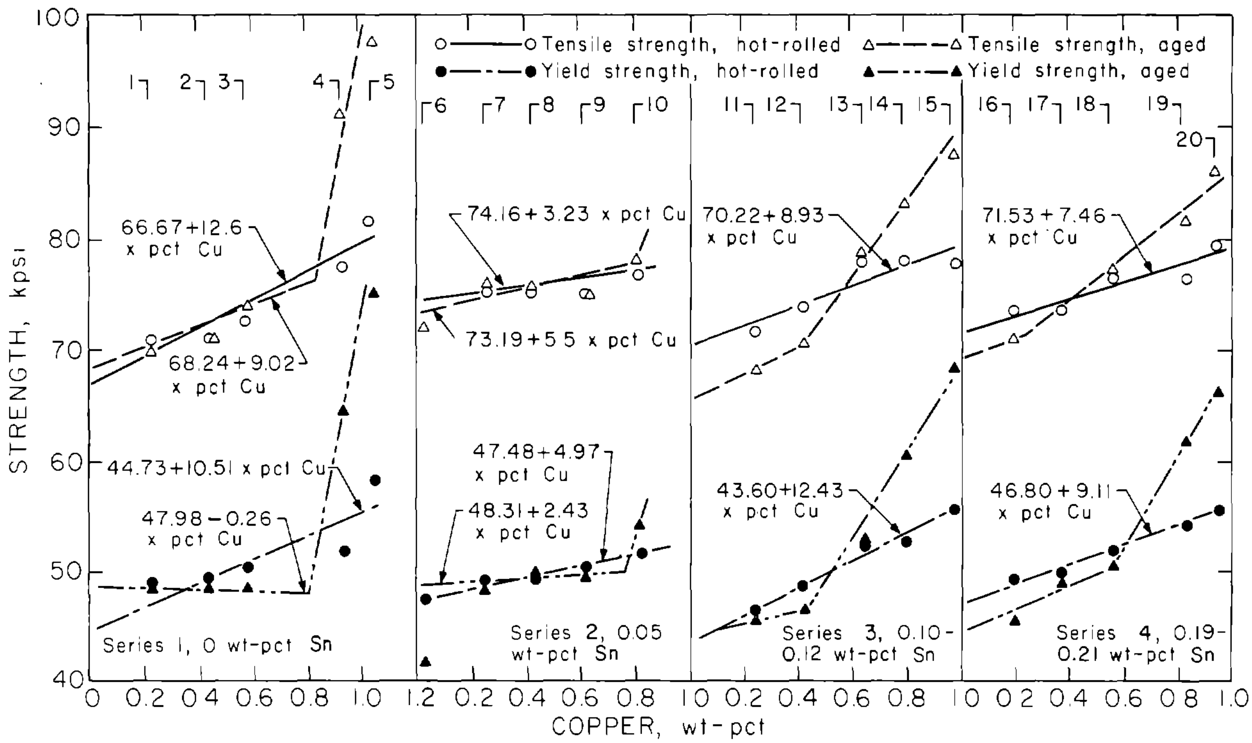

FIGURE 2. - Recalculated yield and tensile strengths of series 1, 2, 3, and 4 steels in hot-rolled and aged conditions.

2. Tin lowers the copper content at which strengthening by copper precipitation starts. The lowering may be caused by tin decreasing the solubility of copper in steel (14-15).

3. At the 1.0 wt-pct Cu level, increasing tin content decreases the strength of copper-precipitation-strengthened steels. The decrease in strength may be due to tin promoting the formation of fewer copper-precipitate nucleation sites and their preferential formation in ferrite grains, which will be further discussed.

Impact Properties

The effects of tin and copper on the energy absorbed and the percent ductile fracture on impact testing specimen at room temperature are given in table B-1 and plotted in figure 3. The data for each steel are an average of two or three specimens. From the plotted data in figure 4, the following was concluded:

1. The energies absorbed during rupturing of steels in the same condition and containing similar copper contents tended to decrease with increasing tin contents (in agreement with Thwaites, 19).

The dramatic exception, for reasons unknown, was steel 19 of series 4 in both conditions. The reason why the energies absorbed in series 1 steels

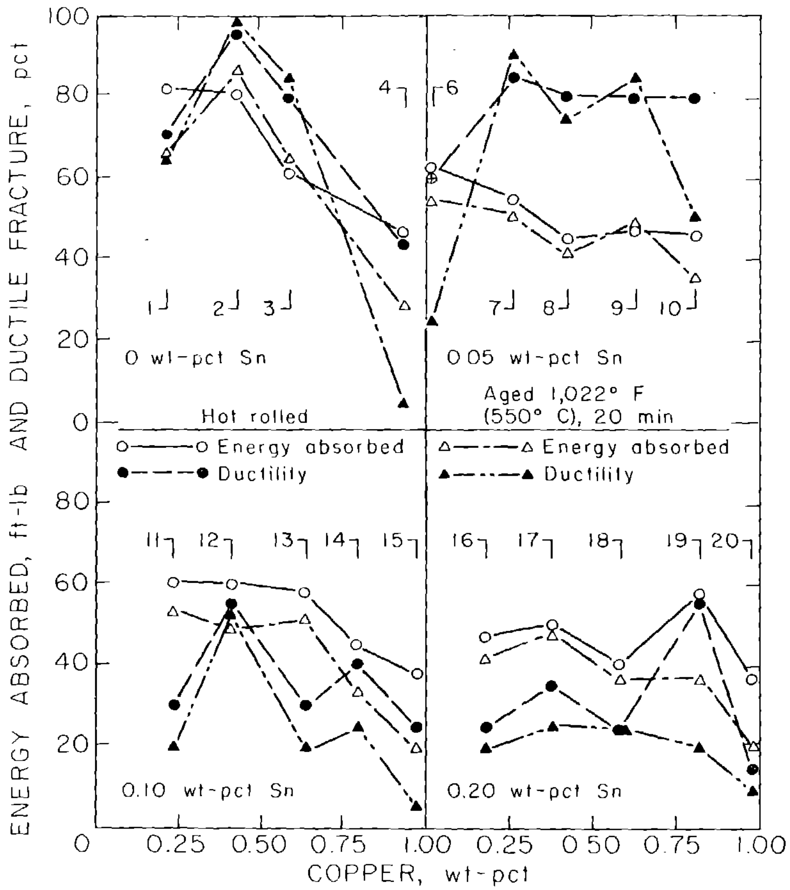

FIGURE 3. - Charpy impact test results for steel specimens broken at 77° F (25° C).

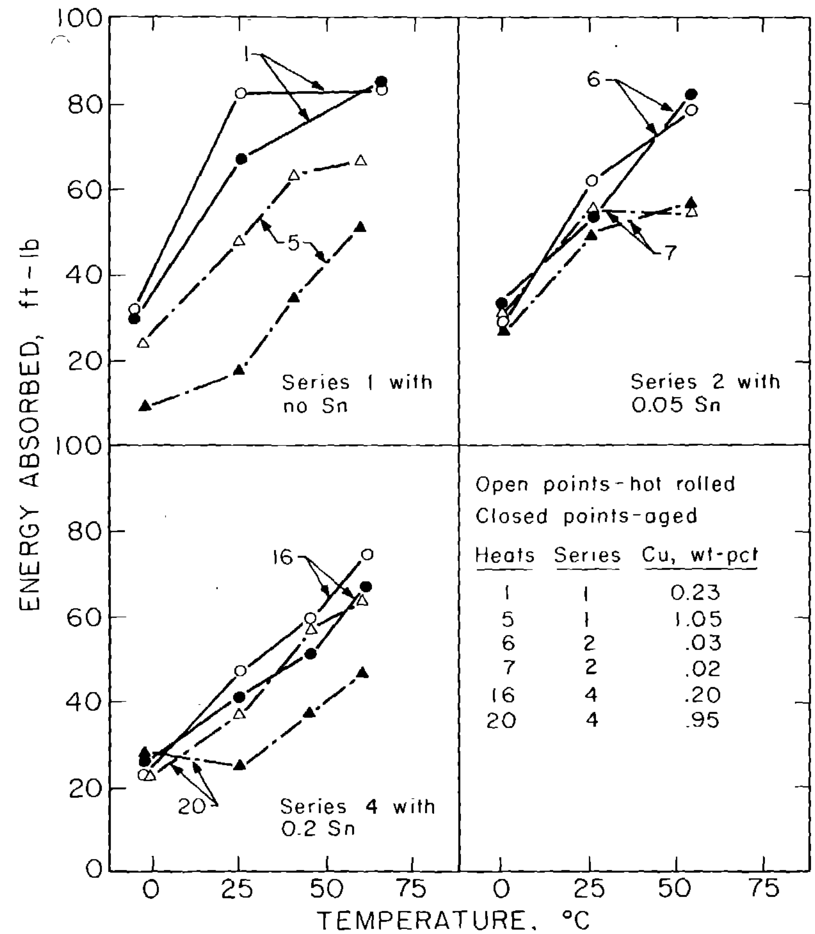

FIGURE 4. - Energy absorbed during testing impact specimens over a range of temperatures.

containing no tin did not continue to increase with increasing copper contents is also not known. This trend was previously observed (4) for steels containing similar silicon contents and no tin, but which contained lower manganese contents, 0.35 to 0.55 wt-pct.

2. The energies absorbed for hot-rolled and aged steels containing the same tin content were similar except for the aged steels containing the larger copper contents, which were lower. The lower absorbed energies are typical for copper-precipitation-strengthened steels.

3. The percent ductile fracture of the broken specimens tended to be maximum at 0.25 to 0.40 wt-pct Cu at all tin contents. Also the ductility of series 2 steels containing more than about 0.6 wt-pct Cu was greater than the other steel series with similar copper content.

The effect of tin and copper on the notch toughness of hot-rolled and aged steels of series 1, 2, and 4 over a range of temperatures is given in table B-2; many selected data are plotted in figure 4. The notch toughness of steels 2, 3, and 4 of series 1 (containing no tin) were not determined because previous work (4) on copper-bearing steels showed that the toughness did not change significantly until more than 0.8 wt-pct Cu was present and aged. The data for 0.05 wt-pct Sn steels 8, 9, and 10 of series 2 were not plotted because their toughness values were very similar to that of steel 7. For 0.20 wt-pct Sn steels 17, 18, and 19 of series 4, the toughness values were determined, but the data were not presented because the values were almost identical with that of steel 20. The following summary of conclusions was deduced from figure 4.

Absorbed Energy

1. The absorbed energy of the steels of series 1, 2, and 4 at low temperatures was not significantly affected by tin, but it was lowered by increasing tin contents at the higher temperatures. The values for any steel of these series were equal to or greater than impact values (20 ft-lb) observed (4) for steels containing 0.3 wt-pct C and up to 1.0 wt-pct Cu.

2. With few exceptions, the impact energy absorbed was lower for aged steels.

Ductile-Brittle Transition Temperature (DBTT)

The DBTT of series 1, 2, and 4 steels were similar (DBTT was considered to exist at the highest test temperatures shown, when 100 pct ductile fracturing occurred). However, based on the one high-temperature test for each steel, the DBTT of steels containing 0.05 wt-pct Sn (series 2) appeared to be lower.

The effect of normalizing heat treatments on the notch toughness of hot-rolled steels containing zero and 0.2 wt-pct Sn is shown in figure 5. The data indicates that the absorbed energies of each steel were increased slightly but that no significant lowering of the DBTT was achieved. Because

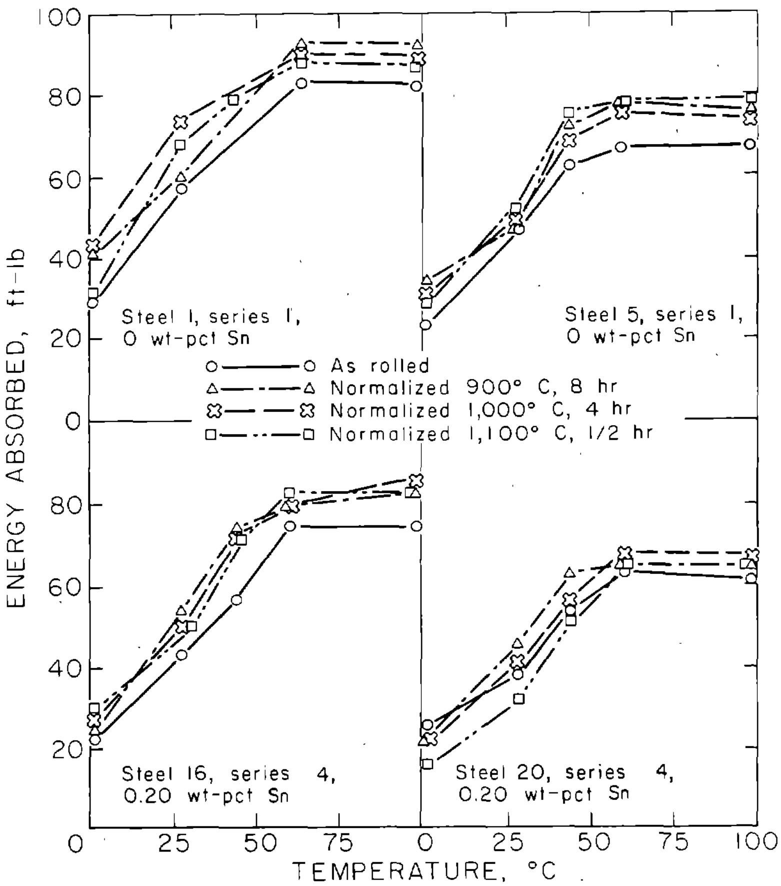

FIGURE 5. - Effect of normalizing heat treatments on notch toughness of steels.

of these limited improvements, such a treatment would not normally justify the cost.

Shelmerdine (16) demonstrated that the impact properties of steels can be improved by quenching treatments. On water quenching from 1,202° F (650° C) a hot-rolled steel containing 0.15 wt-pct C and 0.6 wt-pct Sn, the impact strength was doubled and the DBTT was lowered considerably. The impact properties of steels containing combinations of tin and copper also may be similarly improved by water quenching. However, this treatment was not studied in the present investigation because it is not a practical procedure for most hot-rolled products. The difficulty is the distortion that may result from the treatment.

As for most steels, selection of composition limits depends upon the acceptable impact properties established. The tests did indicate that for hot-rolled steels containing 0.25 to 0.40 wt-pct Si (series 1, 2, 3, and 4), all the steels containing up to 1.0 wt-pct Cu and up to 0.2 wt-pct Sn would be satisfactory at 68° F (20° C) for a minimum absorbed energy of 30 ft-lb. However, aged steels containing over about 0.8 wt-pct Cu would not fulfill this impact energy requirement. For 100 pct ductile fracture at 68° F (that is a DBTT at or below that temperature), few of the steels would be satisfactory. The steels containing 0.40 to 0.50 wt-pct Cu and less than 0.1 wt-pct Sn have the best ductility at 68° F.

Microstructure

The brittle and ductile appearing portions of several broken impact specimens were examined by electron microscopy. Plastic-carbon replicas from the fractures were prepared for this purpose. Intergranular fractures were found on the brittle-appearing portion of steels containing tin but not on the brittle portion of steels containing no tin nor on the ductile-appearing portion of any of the steels. Typical intergranular and transgranular quasi-cleavage fractures observed on the brittle fractures of steels containing

0.2 wt-pct Sn and 0.95 wt-pct Cu are illustrated for steel 20 in figure 6. Dimples on the surface of the intergranular fractures suggest the presence of intergranular particles. The number of intergranular fractures appeared to increase with increasing tin contents.

Dislocation tangles and fine pearlite colonies were noted by transmission, electron-microscopy examination of all the hot-rolled steels. They were probably caused by the low finishing rolling temperature, 1,562° F (850° C) The austenite-austenite + alpha solvus is about 1,526° F (830° C) at 0.2 wt-pct C. The removal of the tangles on normalizing probably accounts for the small improvement in the impact toughness of the normalized steels shown in figure 5.

Intergranular particles, as illustrated in figure 7, also were found along some grain boundaries by transmission, electron-microscopy examination of steels containing tin, in both the hot-rolled and aged conditions. The discontinuous particles, which may be carbides, could weaken the grain boundaries during impact testing and promote the formation of intergranular ruptures. Sullivan (18) theorizes that tin-rich areas may tend to reject carbon in a similar manner to that observed in phosphorous-rich areas of iron-carbon-phosphorous alloys. This conclusion is derived by comparison of the similar restricted gamma loops of iron-rich alloys of tin and phosphorous.

Tin also affected the density of copper precipitates along the ferrite grain boundaries and in the ferrite of the pearlite colonies. Copper precipitates of a similar density formed uniformly throughout the structure of a steel (4) containing 0.93 wt-pct Cu and no tin when aged at 1,022° F (550° C) for 12 hr. After a similar treatment of a steel (20) containing 0.95 wt-pct Cu but with 0.19 wt-pct Sn, a lower density of copper precipitates was found along the grain boundaries and in the ferrite of the pearlite colonies, as illustrated in figure 8. The reason for the lower density at these structural zones is not known.

Metallographically prepared mounts (polished) of hot-rolled steels 16 and 20, containing 0.20 and 0.90 wt-pct Cu, respectively, and 0.2 wt-pct Sn were electron-beam microprobe analyzed for tin segregation. No tin concentration, which may promote intergranular fractures (16, 19), was found along grain boundaries. However, these studies do not mean that intergranular segregation does not occur, as segregation may occur in a zone too narrow to detect. Banding segregation was found, which varied from 0.09 to 0.47 wt-pct tin in steel 20. This amount of segregation probably originated during solidification. Based on the iron-tin phase diagram (9), the first metal to solidify would be relatively free of tin while the last to solidify would be higher than the liquid metal. Thus, the interdendrite areas would contain a high percentage of tin. Long soaking periods prior to rolling may reduce the severity of tin segregation, but it is doubtful if it could be reduced sufficiently to justify the cost.

FIGURE 6. - Intergranular and cleavage fractures in the brittle portion of a broken impact specimen from steel 20 containing 0.19 wt-pct Sn and 0.95 wt-pct Cu (X 2,700).

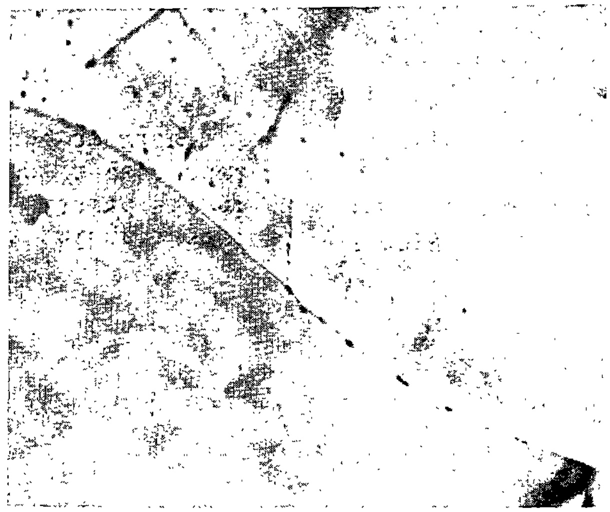

FIGURE 7. - Particles along grain boundary of hot-rolled steel (20) containing 0.2 wt-pct Sn (X 50,000).

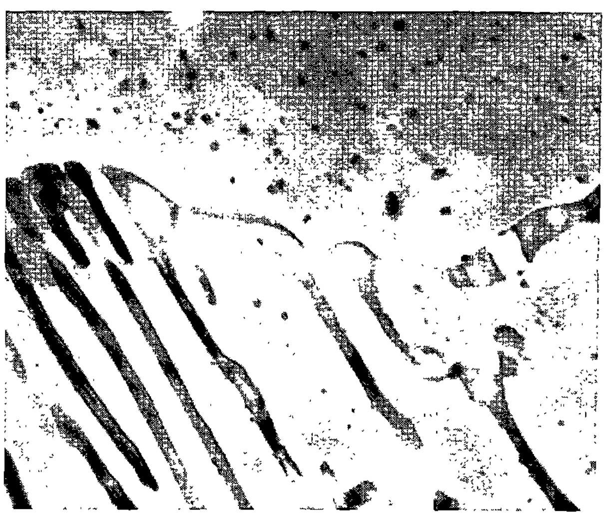

FIGURE 8. - Precipitates in ferrite grain but not in pearlite colony of steel 20 after aging at 1,022° F (550° C) for 12 hr (X 50,000).

CONCLUSIONS

In general, tin contents of up to 0.2 wt-pct proved to be detrimental to selected mechanical properties of wrought, copper-containing, 0.2 wt-pct C steels. The copper precipitation, hardening response of steels containing 1 wt-pct Cu (the largest content studied) is lowered with increasing tin contents and rising aging temperatures for steels treated at 932° to 1,112° F (500° to 600° C, respectively). The tensile properties are similar in the hot-rolled condition for steels containing the same copper content but different tin contents. The copper content (normally 0.8 wt-pct) at which strengths were increased by copper precipitation on aging at 1,022° F (550° C) and the strength obtained above this copper content both become progressively lower with increasing tin contents. Also, impact tests of the steels show the energies absorbed decrease, the ductile-brittle transition temperature increases, and the percentage of intergranular rupture increases with increasing tin contents.

The detrimental effect of tin on copper-containing steels is believed due to solubility and segregation effects. The lower hardness and strength of copper precipitation-treated steels is most likely due to tin lowering the solubility of copper in steel and formation of fewer precipitate nuclei than normally form. Low impact strengths are probably due to preferential tin concentration along grain boundaries.

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APPENDIX A. - TENSILE TEST DATA

TABLE A-1. - Tensile data for hot-rolled steels

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 1											
1......	0.23	0	0.40	48.5	+0.7L	72.7	-0.1L	25	0L	48	0L
				49.5	-.8T	69.7	+.2T	25	-1T	58	+1T
				48.6		72.5		24		52	
				46.4		70.4		24		55	
				48.3(av)		71.3(av)		25(av)		53(av)	
2......	.44	0	.32	47.3	-.1L	70.4	+.2L	26	+1L	55	0L
				48.0	+.1T	70.0	-.2T	32	-2T	57	0T
				47.1		70.4		25		57	
				48.7		69.3		27		54	
				47.8(av)		70.0(av)		28(av)		56(av)	
3......	.58	0	.28	52.1	+.4L	73.8	-.6L	24	+1L	51	+1L
				54.1	-.5T	75.7	+.5T	25	0T	56	0T
				52.5		76.3		23		53	
				51.9		75.5		24		52	
				52.7(av)		75.4(av)		24(av)		53(av)	
4......	.93	0	.36	54.9	+.8L	78.6	0L	22	0L	56	+1L
				54.2	-.7T	79.3	+.1T	24	0T	52	-1T
				53.7		79.1		23		53	
				52.4		79.0		23		51	
				53.8(av)		79.0(av)		23(av)		53(av)	
5......	1.05	0	.27	55.4	+.6L	77.4	-.6L	22	+2L	45	-3L
				57.2	-.7T	79.6	+.5T	24	-2T	49	-3T
				54.9		79.4		20		48	
				55.1		80.0		17		33	
				55.7(av)		79.1(av)		21(av)		44(av)	
SERIES 2											
6......	0.03	0.05	0.39	55.8	+5.3L	95.8	+9.1L	33	0L	53	-2L
				59.5	-5.3T	96.2	-9.1T	32	0T	51	+3T
				46.3		77.5		34		52	
				47.9		78.0		31		61	
				52.4(av)		86.9(av)		33(av)		54(av)	
7......	.26	.05	.26	49.4	-.1L	75.3	+.1L	27	+6L	57	+5L
				51.1	+.1T	76.7	-.1T	33	-6T	61	-5T
				49.5		75.8		20		50	
				51.5		75.7		16		48	
				50.4(av)		75.9(av)		24(av)		54(av)	
8......	.43	.05	.34	50.8	-.7L	78.1	+.5L	23	+2L	56	-7L
				49.4	+.8T	76.7	-.4T	22	-1T	56	+7T
				50.8		75.7		17		44	
				52.3		77.2		23		40	
				50.8(av)		76.9(av)		21(av)		49(av)	

See footnotes at end of table.

TABLE A-1. - Tensile data for hot-rolled steels--Continued

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 2--Continued											
9.....	0.62	0.05	0.36	54.5	+0.5L	79.7	+0.3L	29	0L	57	+6L
				53.5	-.5T	79.0	-.3T	28	0T	58	-5T
				53.2		78.7		28		44	
				52.7		78.9		30		49	
				53.5(av)		79.1(av)		29(av)		52(av)	
10.....	.81	.05	.37	56.2	+.8L	81.4	+.7L	28	+2L	58	+6L
				55.9	-.7T	81.3	-.6T	27	-1T	56	-6T
				53.7		80.1		25		56	
				55.5		80.1		25		34	
				55.3(av)		80.7(av)		26(av)		51(av)	
SERIES 3											
11.....	0.25	0.12	0.37	48.7	+0.9L	73.0	0L	31	+3L	69	+4L
				49.1	-.9T	73.6	-.1T	30	-2T	57	-5T
				46.8		73.1		27		55	
				47.3		73.3		22		53	
				48.0(av)		73.3(av)		28(av)		59(av)	
12.....	.42	.12	.40	52.9	-.1L	77.9	-.5L	30	+1L	55	+6L
				52.1	+.2T	76.9	+.5T	26	-2T	58	-5T
				51.0		77.9		24		44	
				54.5		78.9		26		48	
				52.6(av)		77.9(av)		27(av)		51(av)	
13.....	.65	.12	.39	53.5	+1.1L	76.4	-.6L	26	+1L	55	+3L
				54.5	-1.1T	77.6	+.6T	29	0T	58	-3T
				48.5		78.4		28		49	
				55.1		78.0		26		52	
				52.9(av)		77.6(av)		27(av)		54(av)	
14.....	.80	.10	.33	55.2	+1.2L	80.1	-.4L	23	+1L	52	+1L
				56.5	-1.2T	79.4	+.5T	22	-1T	48	0T
				53.4		80.2		19		49	
				53.5		81.2		23		49	
				54.7(av)		80.2(av)		22(av)		49(av)	
15.....	.98	.10	.33	60.2	+1.6L	82.3	+1.1L	24	0L	56	+4L
				57.8	-1.5T	79.0	-1.1T	22	0T	55	-3T
				56.4		79.0		23		50	
				55.4		78.0		22		47	
				57.4(av)		79.6(av)		23(av)		52(av)	
SERIES 4											
16.....	0.20	0.19	0.40	52.8	+0.3L	77.0	-0.3L	26	+2L	53	+4L
				55.2	-.3T	78.3	+.3T	29	-1T	54	-3T
				52.4		78.1		26		46	
				54.3		78.5		24		47	
				53.7(av)		78.0(av)		26(av)		50(av)	

See footnotes at end of table.

TABLE A-1. - Tensile data for hot-rolled steels--Continued

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 4--Continued											
17.....	0.38	0.21	0.38	49.9	+0.9L	73.4	-0.7L	25	0L	53	+3L
				52.1	-.9T	72.2	+.7T	22	-1T	50	-3T
				50.2		74.0		22		44	
				48.1		74.3		24		47	
				50.1(av)		73.5(av)		24(av)		49(av)	
18.....	.57	.21	.34	53.9	+.8L	78.4	-.3L	24	-1L	53	+1L
				55.4	-.8T	78.8	+.4T	24	+2T	50	-1T
				54.6		78.4		28		51	
				51.5		80.0		25		49	
				53.9(av)		78.8(av)		25(av)		51(av)	
19.....	.83	.19	.41	59.0	+.1L	80.9	+.8L	26	+3L	57	+3L
				54.2	-.1T	77.4	-.8T	25	-2T	54	-2T
				56.1		77.8		21		52	
				56.6		77.4		21		49	
				56.5(av)		78.4(av)		23(av)		53(av)	
20.....	.95	.19	.33	59.2	-.6L	81.9	-1.3L	22	+1L	45	-3L
				54.6	+.5T	78.4	+1.2T	19	-0T	39	+3T
				57.7		82.5		19		48	
				58.3		83.1		20		46	
				57.5(av)		81.5(av)		20(av)		45(av)	

Ind--Individual tests.
Dev--Deviation of total average from average of results for each direction.
[1]First two results in individual (Ind) columns are longitudinal properties and the second two results are transverse; the fifth item is an average.
[2]L and T indicate longitudinal and transverse, respectively.

TABLE A-2. - Tensile data for aged steels

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 1											
1.....	0.23	0	0.40	48.0	-0.5L	71.7	-0.6L	24	-6L	55	-1L
				46.0	+.5T	69.0	+.7T	28	+7T	58	+1T
				50.4		72.7		37		59	
				49.6		70.7		-		-	
				48.5(av)		71.0(av)		30(av)		58(av)	
2.....	.44	0	.32	45.8	+.4L	69.2	-.3L	34	+1L	56	-1L
				46.8	-.4T	70.1	+.4T	30	+1T	49	+1T
				46.0		70.4		30		53	
				45.0		69.4		30		57	
				45.9(av)		70.0(av)		31(av)		54(av)	

See footnotes at end of table.

TABLE A-2. - Tensile data for aged steels--Continued

Steel	Composition, wt-pct Cu	Sn	Si	Yield strength, kpsi Ind[1]	Dev[2]	Tensile strength, kpsi Ind[1]	Dev[2]	Elongation, pct Ind[1]	Dev[2]	Reduction in area, pct Ind[1]	Dev[2]
SERIES 1--Continued											
3.....	0.58	0	0.28	51.4	-1.3L	75.5	-1.4L	30	-1L	45	-1L
				49.8	+1.3T	73.8	+1.5T	29	+1T	59	+1T
				52.5		77.6		29		52	
				53.9		77.6		33		56	
				50.6(av)		76.1(av)		30(av)		53(av)	
4.....	.93	0	.36	66.1	+.1L	90.8	-.3L	27	+2L	51	+0L
				66.3	-.1T	91.2	+.3T	26	-3T	46	+1T
				65.9		93.4		24		51	
				66.1		90.1		22		49	
				66.1(av)		91.3(av)		26(av)		49(av)	
5.....	1.05	0	.27	70.1	-1.4L	93.9	-.2L	22	+2L	53	+3L
				72.3	+1.3T	96.7	+.2T	22	-2L	43	-3T
				73.8		96.1		20		51	
				74.0		95.3		17		34	
				72.6(av)		95.5(av)		20(av)		45(av)	
SERIES 2											
6.....	0.03	0.05	0.39	47.6	+0.7L	77.7	-0.3L	29	0	52	-2L
				47.3	-.6T	76.8	+.2T	29		53	+2T
				46.4		77.7		29		59	
				45.9		77.7		29		55	
				46.8(av)		77.5(av)		29(av)		55(av)	
7.....	.26	.05	.26	47.6	-1.9L	77.7	+.4L	29	+3L	52	+3L
				47.3	+2.0T	76.8	-.4T	29	-2T	53	-2T
				50.2		75.4		24		45	
				52.5		77.5		23		50	
				49.4(av)		76.9(av)		26(av)		50(av)	
8.....	.43	.05	.34	47.1	-1.2L	74.1	-1.0L	17	-2L	52	+1L
				52.8	+1.2T	78.5	+1.1T	20	+3T	48	-1T
				51.3		77.3		23		51	
				53.4		79.4		24		44	
				51.2(av)		77.3(av)		21(av)		49(av)	
9.....	.62	.05	.36	52.5	-.5L	79.6	+.4L	27	+3L	54	+5L
				52.5	+.5T	79.6	-.4T	32	-3T	52	-6T
				53.5		78.8		24		36	
				53.5		78.8		24		48	
				53.0(av)		79.2(av)		27(av)		48(av)	
10.....	.81	.05	.37	57.8	-.8L	80.6	-1.7L	20	-4L	35	-8L
				56.8	+.8T	80.8	+1.7T	17	+5T	41	+8T
				58.8		84.9		29		56	
				59.0		83.4		27		52	
				58.1(av)		82.4(av)		23(av)		46(av)	

See footnotes at end of table.

TABLE A-2. - Tensile data for aged steels--Continued

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 3											
11.....	0.25	0.12	0.37	44.5	+0.5L	72.0	+2.0L	35	+5L	51	-5L
				45.1	-.5T	72.1	-2.0T	35	-5T	55	+5T
				45.3		67.5		25		59	
				46.3		68.1		26		63	
				45.3(av)		70.0(av)		30(av)		57(av)	
12.....	.42	.12	.40	52.8	+2.3L	77.6	+3.0L	25	-3L	43	-7L
				52.9	-2.3T	77.8	-3.1T	-	+2T	-	+6T
				48.1		71.7		32		55	
				48.4		71.5		28		57	
				50.6(av)		74.7(av)		28(av)		50(av)	
13.....	.65	.12	.39	52.9	-1.6L	76.5	-1.6L	25	-2L	51	-3L
				50.6	+1.7T	77.0	+1.7T	24	+2T	51	+3T
				50.1		78.9		29		55	
				56.0		81.2		29		58	
				53.4(av)		78.4(av)		27(av)		54(av)	
14.....	.80	.10	.33	62.9	-.2L	85.7	-.3L	20	-1L	44	-1L
				62.3	+.1T	86.7	+.2T	22	+2T	45	+1T
				63.1		85.6		24		55	
				62.7		85.4		24		37	
				62.8(av)		85.7(av)		22(av)		45(av)	
15.....	.98	.10	.33	68.2	-2.3L	86.9	-2.1L	21	-1L	51	-3L
				67.7	+2.4T	87.8	+2.1T	18	+0T	47	+4T
				73.6		93.5		26		57	
				71.8		89.7		17		51	
				70.3(av)		89.5(av)		21(av)		52(av)	
SERIES 4											
16.....	0.20	0.19	0.40	51.4	+1.3L	77.5	+0.1L	29	+2L	50	+2L
				51.6	-1.3T	77.4	-0T	34	-2T	57	-2T
				49.3		73.1		31		48	
				48.7		73.5		29		48	
				50.3(av)		75.4(av)		32(av)		52(av)	
17.....	.38	.21	.39	48.8	-.8L	73.9	-.1L	24	-3L	52	-4L
				48.0	+.8T	73.9	+.1T	24	+3T	38	+4T
				49.6		73.4		26		56	
				50.4		73.9		34		49	
				49.2(av)		73.8(av)		27(av)		49(av)	
18.....	.57	.21	.34	54.3	+.9L	79.4	+.3L	26	-2L	38	-3L
				53.1	-.9T	79.9	-.2T	24	+2T	45	+3T
				53.6		78.2		27		41	
				50.1		80.1		32		56	
				52.8(av)		79.4(av)		27(av)		45(av)	

See footnotes at end of table.

TABLE A-2. - Tensile data for aged steels--Continued

Steel	Composition, wt-pct			Yield strength, kpsi		Tensile strength, kpsi		Elongation, pct		Reduction in area, pct	
	Cu	Sn	Si	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]	Ind[1]	Dev[2]
SERIES 4--Continued											
19.....	0.83	0.19	0.41	63.1	-0.7L	83.1	-0.9L	22	+0L	49	+3L
				63.8	+.7T	83.8	+.8T	22	+0T	50	-3T
				64.3		83.6		24		38	
				65.5		86.9		19		50	
				64.2(av)		84.4(av)		22(av)		47(av)	
20.....	.95	.19	.33	67.3	-1.0L	87.8	-.2L	23	+2L	48	+2L
				67.8	+.9T	88.5	+.3T	24	-2T	44	-2T
				69.4		88.9		23		41	
				69.5		85.4		18		43	
				68.5(av)		88.4(av)		22(av)		44(av)	

Ind--Individual tests.

Dev--Deviation of total average from average of results for each direction.

[1] First two results in individual (Ind) columns are longitudinal properties and the second two results are transverse; the fifth item is an average.

[2] L and T indicate longitudinal and transverse, respectively.

APPENDIX B.--CHARPY IMPACT TEST DATA

TABLE B-1. - Charpy impact test results for specimens broken at 77° F (25° C)

Series number and contents	Heat	Charpy impact test			
		Hot-rolled		Aged[1]	
		Energy absorbed, ft-lb	Ductile fracture, pct	Energy absorbed, ft-lb	Ductile fracture, pct
1--with no Sn, 0.25 to 0.40 wt-pct Si, and up to 1.0 wt-pct Cu.	1	82	70	67	65
	2	81	95	86	100
	3	61	80	67	85
	4	46	45	29	5
2--with 0.05 wt-pct Sn, 0.25 to 0.40 wt-pct Si, and up to 1.0 wt-pct Cu.	6	62	60	54	25
	7	55	85	51	90
	8	45	80	43	75
	9	47	80	49	85
	10	46	80	37	50
3--with 0.10 wt-pct Sn, 0.25 to 0.40 wt-pct Si, and up to 1.0 wt-pct Cu.	11	60	30	54	20
	12	60	55	55	55
	13	58	30	51	20
	14	45	40	34	25
	15	39	25	20	5
4--with 0.20 wt-pct Sn, 0.25 to 0.40 wt-pct Si, and up to 1.0 wt-pct Cu.	16	47	25	41	20
	17	50	35	49	25
	18	40	25	37	25
	19	58	55	35	20
	20	37	15	25	10

[1]Heat treated at 1,022° F (550° C)--20 min.

TABLE B-2. - Charpy impact test results at various temperatures of hot-rolled and aged steels

Steel	Content, wt-pct			Hot-rolled			Aged		
	Sn	Cu	Si	Temp, ° C	Energy absorbed, ft-lb	Ductile fracture, pct	Temp, ° C	Energy absorbed, ft-lb	Ductile fracture, pct
SERIES 1									
1......	Nil	0.23	0.40	-4	32	10	-4	30	10
				25	82	70	27	67	65
				65	83	100	60	84	100
5......	Nil	1.05	.27	-2	24	5	-3	9.5	0
				25	48	20	27	18	0
				45	63	90	63	35	40
				61	67	100	102	54	100
SERIES 2									
6......	0.05	0.03	0.39	0	28	10	0	34	10
				25	62	60	25	54	25
				53	79	100	51	82	95
7......	.05	.26	.26	-1	32	20	-1	29	10
				25	55	85	25	50	90
				53	56	100	51	57	100
8......	.05	.43	.34	-1	28	20	-2	25	20
				25	45	80	25	43	75
				53	59	100	51	59	100
9......	.05	.62	.36	-1	27	20	-1	28	20
				25	47	80	25	49	85
				52	54	100	52	57	100
10......	.05	.81	.37	-1	27	20	-2	22	10
				25	46	80	25	37	50
				52	58	100	52	56	100
SERIES 4									
16......	0.19	0.20	0.40	-2	23	10	-2	26	5
				25	47	25	27	41	20
				45	57	70	44	51	50
				61	75	100	59	67	100
20......	.19	.95	.33	-2	23	10	-2	26	5
				25	37	15	27	25	10
				45	58	90	45	38	50
				60	64	100	60	47	95

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