High Performance Copper-Precipitation-Hardened Steel

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Introduction

This paper presents data for a high performance hot-rolled and air-cooled low-carbon, copper-precipitation-hardened steel developed at Northwestern University (NUCu steel). The approach taken for developing a tough, strong, improved weldability and weatherability steel [1-4] was to derive additional strength by copper precipitation hardening which occurs during air cooling. Further increase in strength is achieved by aging after air cooling or normalizing. Nickel is present to prevent hot-shortness during hot rolling but also gives solid solution strengthening. Niobium was added to reduce grain size. The steel has very low carbon equivalent weldability index.

The initial development was done with laboratory heats of steel that were produced at Inland Steel Company and US Steel Research and Technology Center. Two commercial 80,000-kg heats were produced at Oregon Steel Mills (OSM) to investigate the steel production under industrial conditions and for bridge repair. These heats were cast into slabs by a bottom pour process. Results of the previous work were published earlier [1-4]. Recently a slab previously cast at OSM was hot-rolled at U.S.Steel Gary Works. The production and properties of plates made from this slab are presented and discussed in this paper.

Experiments

The cast steel slab, 178-mm (7-inch-) thick, received from OSM was cut in two and hot-rolled into plates of 25.4-mm (1 inch) and 19.1 mm (0.75-inch) thickness. The cast slabs were reheated to 1066°C (1950°F) and then rolled. The first pass for the 25.4-mm-(1-inch-) thick plate was done after the slab was cooled down to 973°C (1783°F). The finishing hot-rolling temperature for this plate was 937°C (1719°F). The second slab was first rolled down to 96.3 mm (3.79-inches) and then it was reheated to 1277°C(2300°F). Before rolling was continued the slab was cooled to 1039°C (1902°F) and then rolled down to 19.1 mm (0.75 inches). The finishing rolling temperature for this plate was 937°C (1719°F), the same as for the 25.4-mm- (1-inch) thick plate. The plates were air cooled after hot rolling. Portions of the plates were cut for specimen preparation. Some of these were austenitized at 900°C(1650°F) and air-cooled or quenched. The time at temperature for austenitizing and/or aging was 40 minutes per inch thickness.

Round tensile specimens with a gauge section of 50.8 mm (2 inches) (ASTM E8 Standard) and Charpy specimens (ASTM E23 Standard) were machined in longitudinal direction from the quarter thickness of the plates and tested. For each plate multiple specimens were tested with very little variation observed. A metallographic study was also made.

Results and Discussion

Chemical Composition. Chemical composition of the steel heat is shown in the Table 1.

Mechanical Properties. Results of the mechanical testing are summarized in the Tables 2-5. Tables 2 and 3 demonstrate the effects of different treatments on mechanical and fracture properties respectively of the 19.1-mm- (0.75-inch)-thick plate. As-rolled the yield stress is 503 MPa (73 Ksi) and 567 MPa (82 Ksi) ultimate tensile strength. The elongation exceeds 30%. The Charpy absorbed impact energy is remarkably high down to –40°C (-40°F), the lowest temperature used. Previously we found[2-4] that the Charpy absorbed impact energy is reduced significantly if the rolling temperature exceeded 1150°C (2100°F). This was attributed to the formation of Widmanstatten ferrite at high temperatures. Despite the fact that the second reheat temperature for the slab used to roll this plate was 1277°C(2300°F) cooling the slab down to 1039°C (1902°F) before continuing the rolling gave 161J (118 ft-lb) Charpy absorbed impact energy at -40°C (-40°F). Microstructural examination did not find any Widmanstatten ferrite present in the steel.

Aging of as-rolled 19.1-mm- (0.75-inch)-thick plate increased the strength of the steel by about 35-45 MPa (5-7 Ksi) with only a very slight reduction in the Charpy absorbed impact energy. Normalizing reduced the strength, but significantly increased the Charpy absorbed impact energy. Aging of the normalized steel significantly increased the strength with some reduction of the Charpy absorbed impact energy. Quenching and then aging of the steel had a significant effect on the properties. The yield strength increased dramatically when the steel was quenched from 900°C (1650°F) and then aged at 524°C (975°F) but the Charpy impact energy was reduced to 64 J (47 ft-lb) at -40°C (-40°F), still a high value for a structural steel at this low temperature. Increasing the aging temperature reduced the yield strength to about 650 Mpa (95 Ksi) but increased the Charpy impact energy.

Table 1. Composition of the steel (wt.%)

C	Mn	P	S	Si	Cu	Cr	Mo	Nb	Al	Ca
0.06	0.78	0.006	0.005	0.38	1.37	0.06	0.03	0.038	0.029	0.0037

Table 2. Mechanical properties of 19.1 mm (0.75 inch)-thick plate

Plate Condition	*Yield Strength* MPa (Ksi)*	*Tensile Strength (Ksi)*	*Elongation (%)*	*Reduction in Area (%)*
As-Rolled and air cooled	503 (73)	567 (82)	32.2	68.7
As-Rolled & Aged 524°C (975°F)	539 (78)	610 (89)	33.0	64.6
Normalized 900°C (1650°F)	461 (67)	546 (79)	36.2	63.1
Normalized & Aged 524°C (975°F)	557(81)	638 (93)	35.2	66.5
RhQ& Aged 524°C (975°F)	712 (103)	780 (113)	26.3	62.5
RhQ& Aged 552°C (1025°F)	658 (96)	733 (107)	29.8	65.2
RhQ& Aged 579°C (1075°F)	642(93)	716 (104)	29.5	68.0

***** 0.2% offset.

Table 3. Charpy absorbed impact energy of 19.1-mm (0.75-inch)-thick plate

Plate Condition	*Charpy - V- Notch Impact Energy, J (ft –lbs) at temperatures:*			
	-40°C (-40°F)	*-23°C (-10°F)*	*-12°C (+10°F)*	*0°C (+32°F)*
As-Rolled and air cooled	161 (118)	192 (141)	202 (148)	206 (151)
As-Rolled & Aged 524°C (975°F)	149 (109)	164 (120)	173 (127)	179 (131)
Normalized 900°C (1650°F)	233 (171)	242 (177)	255 (187)	257 (188)
Normalized & Aged 524°C (975°F)	126 (92)	153 (112)	165 (121)	176 (129)
RhQ& T 524°C (975°F)	64 (47)	89 (65)	115 (84)	132 (97)
RhQ& T 552°C (1025°F)	124 (91)	143 (105)	152 (111)	169 (124)
RhQ& T 579°C (1075°F)	168 (123)	175 (128)	183 (134)	214 (157)

Results for the 25.4-mm (1-inch)-thick plate, Tables 4 and 5, are similar to those for the 19.1-mm- (0.75-inch)-thick plate. As expected, the strength of 25.4-mm (1-inch)-thick plate is slightly lower. Since copper precipitation is the main strengthening mechanism, slower cooling in a thicker plate leads to larger copper precipitates.

The microstructures are very similar in both steel plates and are functions of heat-treatment. The microstructures of the 25.4-mm (1-inch)-thick plate are shown in Figure 1. The steel has an equaxed ferritic microstructure. In as-rolled, as-rolled and aged, normalized, and normalized and aged conditions pearlite regions are observed. They form bands parallel to the surface of the plates. Pearlite is not present in the quenched and aged steel. While the average grain size is approximately 12-15μm in the as-rolled steel, the grains in quenched and aged steel are significantly smaller, on the order of a few microns. Reduction in grain size contributes to the strength of the steel in addition to strengthening from copper precipitate aging. Copper precipitates could not be observed in optical microscope, they are approximately 3 nm in diameter as determined in the three dimensional atom probe[5].

Table 4. Mechanical properties of 25.4-mm (1-inch)-thick plate

Plate Condition	***Yield Strength* MPa (Ksi)***	***Tensile Strength (Ksi)***	***Elongation (%)***	***Reduction in Area (%)***
As-Rolled and air cooled	465 (68)	547 (80)	32	70
As-Rolled & Aged 524°C (975°F)	625 (91)	665 (97)	26	61
Normalized 900°C (1650°F)	466 (68)	542 (79)	36	72
Normalized & Aged 524°C (975°F)	559 (81)	636 (92)	31	72
RhQ& T 524°C (975°F)	678 (99)	756 (110)	29	68
RhQ& T 552°C (1025°F)	661(96)	737 (107)	28	67
RhQ& T 579°C (1075°F)	615 (89)	682 (99)	29	73

***** 0.2% offset.

Table 5. Charpy absorbed impact energy of 25.4-mm (1-inch)-thick plate

Plate Condition	***Charpy - V- Notch Impact Energy, J (ft–lb) at temperatures:***			
	-40°C (-40°F)	***-23°C (-10°F)***	***-12°C (+10°F)***	***0°C (+32°F)***
As-Rolled and air cooled	161 (118)	187 (137)	221 (162)	228 (167)
As-Rolled & Aged 524°C (975°F)	64 (47)	117 (86)	132 (97)	150 (110)
Normalized 900°C (1650°F)	205 (150)	266 (195)	258 (189)	270 (198)
Normalized & Aged 524°C (975°F)	137 (100)	164 (120)	173 (127)	195 (143)
RhQ& T 524°C (975°F)	96 (70)	124 (91)	167 (122)	202 (148)
RhQ& T 552°C (1025°F)	98 (72)	106 (78)	160 (117)	173 (127)
RhQ& T 579°C (1075°F)	195 (143)	238 (174)	235 (172)	238 (174)

Welding. Due to the very low carbon level and the absence of chromium and molybdenum NUCu steel has a very low carbon equivalent welding criterion. The steel was designed to be welded without pre-heat or post-heat. Previously welding was evaluated without pre-heat or post-heat by a submerged arc (SAW) process and also by a manual process in a construction shop environment (Trinity Bridge and Arlington Construction Companies). Matching consumables were used. No brittle heat-affected zone was formed. These results were confirmed in a welding laboratory at Northwestern University using very high-energy input [2-4].

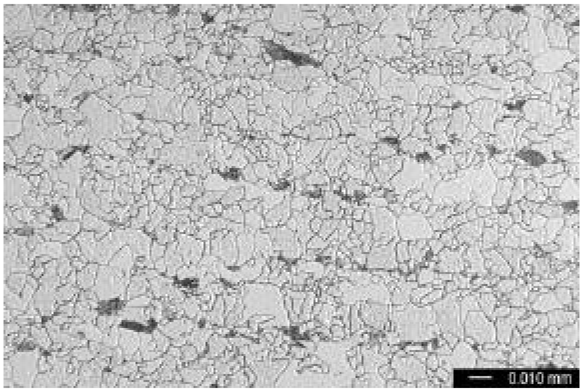
Duplicate GBOP tests conducted earlier at the U.S. Steel Research and Technology Center using a heat input of 1.4 KJ/mm (53 KJ/inch) and low hydrogen AWS E7018 and E9018 electrodes without pre-heat or post-heat did not show weld metal cracks in the welds or base plates.

Stupp Bridge Company, Bowling Green, Kentucky, recently performed a Procedure Qualification (PQR) SAW Test without pre-heat and post-heat using Lincoln LA85 electrodes and Mil800-HPNi flux. The heat input was 2.36 KJ/mm (60 KJ/inch). In fracture tests; at -30°C(-22°F) the average Charpy absorbed impact energy was 124 J (91 ft-lb). The requirement by American Welding Society Standard is 34 J (25 ft-lb) at this temperature.

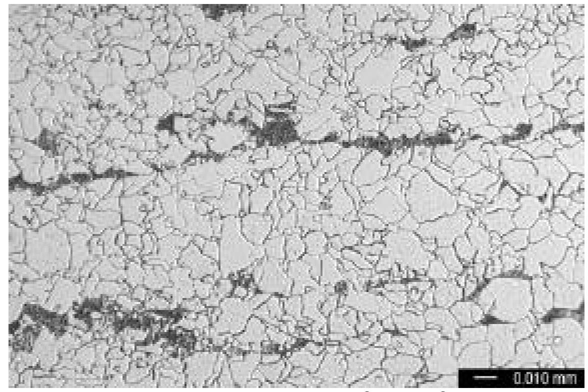
Corrosion Performance. Copper imparts weathering resistance in inland and marine environments and the high copper content in NUCu steel is effective in substantially reducing the weight loss in accelerated weathering tests.

In SAE J2334 standard accelerated tests performed at Bethlehem Steel Corporation by Townsend[7], the weight loss of NUCu steel was compared to that for A36 steel and other weathering steels. Townsend's results are summarized in Figure 2. The thickness loss of A36 steel was133% greater than that of NUCu steel. The thickness losses of A588 weathering steels and HPS70W A709 steel were 69% larger than that of NUCu steel. Using existing data bases corrosion indexes have been established and the index for NUCu steel is far lower than that for any other structural steel[6,7,8].

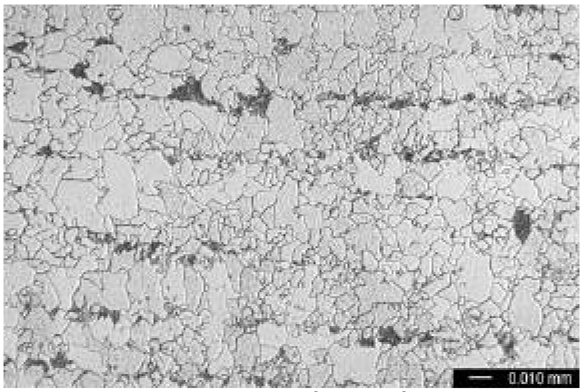
At the present time NUCu steel together with a number of plain carbon and weathering steels are being exposed at different



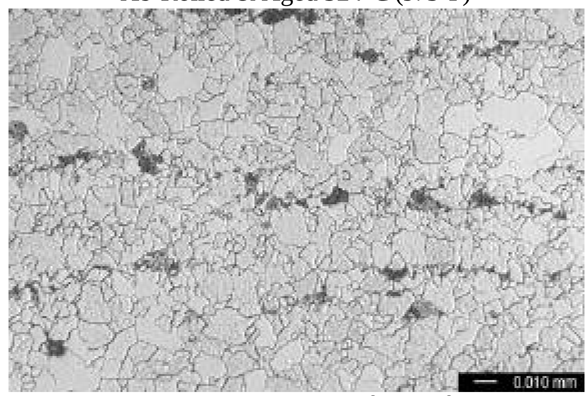
As-Rolled



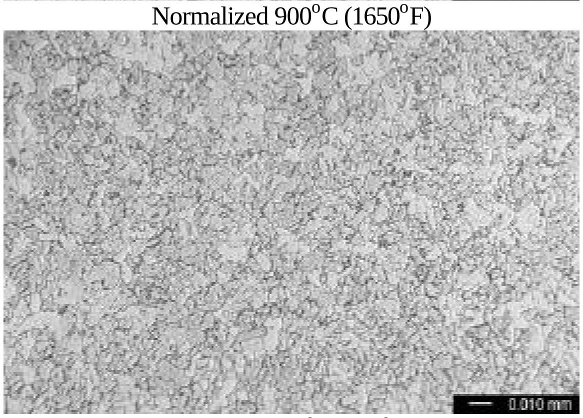
As-Rolled & Aged 524°C (975°F)



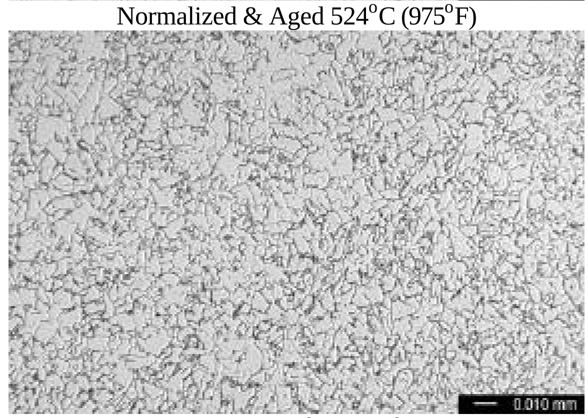
Normalized 900°C (1650°F)



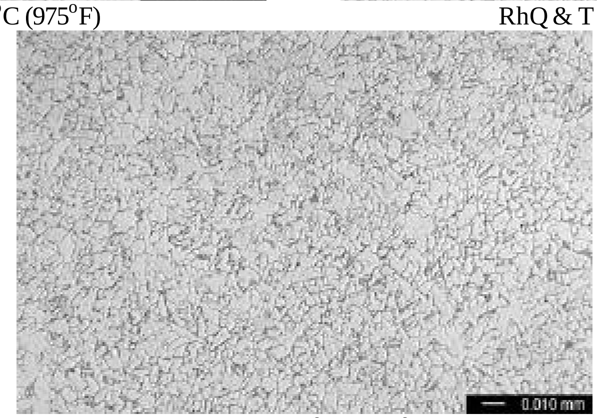
Normalized & Aged 524°C (975°F)



RhQ & T 524°C (975°F)



RhQ & T 552°C (1025°F)



RhQ & T 579°C (1075°F)

Figure 1. Microstructure of 25.4 mm- (1-inch-) thick plate

corrosion sites around the USA to establish the long time weathering resistance but not enough time has elapsed to reach any firm conclusions[7].

The same steel grades were coated with epoxy-based Carboguard 890 paint from Carboline Company, scratched and then tested in a salt-fog chamber (ASTM B-117 Standard, 49.97 g/liter salt solution). The extent of corrosion was measured after exposure at 35°C for 3 weeks. Results of the tests are shown in the Figure 3. The widths of the corroded regions adjacent to the scratches are compared to the weight loss reported by Townsend in Fig. 4. Again NUCu steel showed the best corrosion resistance; the corroded surfaces at the scratches of A36, A588 and HPS 70W A709 steels were 93%, 52% and 54% respectively wider than that of NUCu steel.

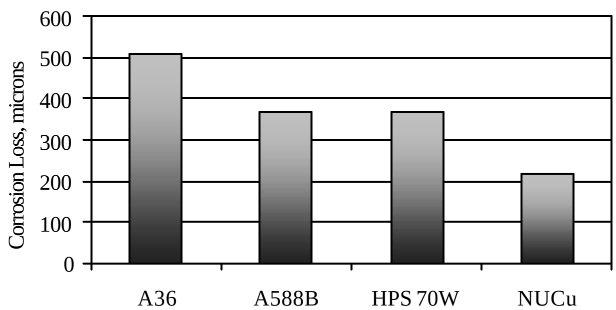


Figure 2. Results of the accelerated corrosion test (automotive SAE J2334 Standard) performed at Bethlehem Steel Company[7]

Figure 3. Painted steel panels after 3 weeks, 35°c exposure in salt-fog chamber (A36; A588; ASTM HPS70W; NUCu (ASTM A710 Grade B) steels)

Acknowledgments

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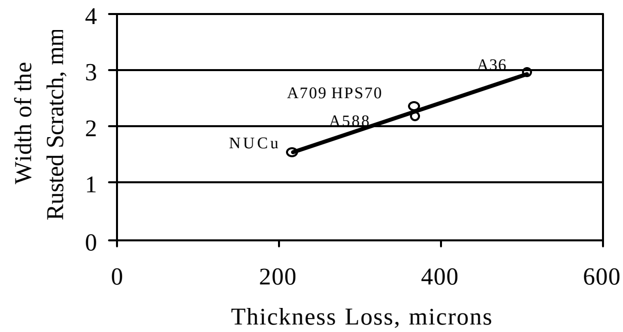

Figure 4. Comparison of the width of the rusted region on the salt sprayed scratched painted steel panels with the thickness loss of the bare steel panels in SAE J2334 tests.

Summary

Copper precipitation strengthening is an alternate route to quench and tempering or thermomechanical processing to a high performance low-carbon 70-grade structural steel. Cast slabs of a NUCu steel 200 mm thick were hot-rolled to 25 and 19 mm thickness and air-cooled. Tensile and Charpy impact tests were done on samples as cooled, aged, normalized, and normalized and aged. With the 25.4-mm- (1-inch-) thick plate aging after air cooling from hot rolling or normalizing was required to reach the desired yield strength level. Particularly noteworthy are the very high Charpy impact energies at cryogenic temperatures. The 19-mm- (0.75-inch-) thick plate successfully passed a PQR welding test without pre-heat or post-heat and with matched welding rods. Corrosion tests on bare and painted panels are reported. The corrosion for NUCu steel was significantly less than that for ordinary weathering steels including the high performance A709W steel.

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