Copper Precipitation Hardened, High Strength, Weldable Steel

by Semyon Vaynman [1], Morris E. Fine [1], Gautam Ghosh [1], and Shrikant P. Bhat [2]

"Materials for the New Millennium," *Proceedings of the 4th Materials Engineering Conference*, ASCE Annual Convention, November 10-14, 1996, Washington, DC, p. 1551.

Abstract

Steel containing 0.03% carbon, 1.35% copper and 0.84% nickel had yield strength in the 540-625 MPa (78-90 Ksi) range depending on thickness, ultimate tensile strength in the 625-690 MPa (90-100 Ksi) range, and 25-30% elongation when air cooled after hot rolling. No brittle heat-affected zone was formed during manual or automatic submerged arc welding without pre-heating or post-heating. The fracture toughnesses in the plate and in the heat-affected zone were excellent.

Introduction

During the past several years an easily weldable, high strength (more than 540 MPa yield), high impact fracture toughness steel (NUCu) has been investigated at Northwestern University with bridge applications in mind. For good weldability without pre-heating and post-heating, the carbon content of the steel was kept low and high strength was achieved by copper precipitation hardening. The steel was designed to be air cooled from hot rolling. Omitting the most expensive alloying elements (Cr and Mo), and eliminating the need for quench and temper heat treatment used in other high strength structural steel alloys reduces the cost of the steel, an important requirement for infrastructure applications.

Experimental Methods

The initial studies at Northwestern University were conducted on six 220 kg laboratory heats prepared at Inland Steel Company's Research Laboratory by vacuum-induction melting. These steel heats, numbered as NUCul through NUCu6 were hot-rolled to 12.7 mm thick plates and air cooled. A commercial 80 ton steel heat was produced at Oregon Steel Mills, Portland, Oregon. The heat was calcium treated for inclusion shape control. Two slabs were cast using Amsted bottom pressure casting process. The slabs were hot-rolled into plates of several thicknesses 12.7 to 25.4 mm (0.5 to I inch) and air cooled. A hot-rolling temperature of 1150°C or less was specified.

The compositions of two laboratory steel heats (NUCu5 and NUCu6) produced by Inland Steel Research Laboratory and the commercial steel produced by Oregon Steel Mills (NUCu-Oregon), are listed in TABLE 1. For good weldability the carbon content in steels was kept low, 0.03 to 0.05%, giving low carbon equivalent (Table 1). Since the steel is not quenched and tempered, Cr and Mo were omitted. Copper concentration was approximately 1.3% to provide targeted better than 485 MPa (70 Ksi) strength through precipitation hardening. Ni was added to prevent hot-shortness during hot rolling. Nb and Ti were added to control grain size during hot rolling and welding.

TABLE 1. Composition of Experimental NUCu5 and NUCu6, and Commercial NUCu-Oregon Steels (Wt.%)

ELEMENT	NUCu5-INLAND	NuCu6-INLAND	NUCu-OREGON
C	0.03	0.05	0.03
Cu	1.29	1.37	1.35
Ni	0.52	0.49	0.84
Mn	0.53	0.56	0.49
Si	0.52	0.43	0.40
Nb	0.06	0.06	0.062

Ti	0.10	0.08	0.03
CE	**0.44**	**0.46**	**0.47**

Carbon Equivalent is based on formula: CE = (C + Mn)/6 + Nb/5 + (Cu + Ni)/15

Flat 6 mm thick tensile specimens with a gauge section of 50 mm (ASTM E8) were machined from the middle thickness of the plates along the rolling direction. Standard size Charpy V-notch specimens (ASTM E23), machined from the middle thickness of the plate, were tested in the transverse orientation over -62 to 24°C (-80 to 75 °F) temperature range.

Plates 15.9 mm (0.625 in) thick were welded manually with JETWELD 100M1MR (MIL 10018) electrode, and automatically using the submerged arc process with LINCOLNWELD LA100 wire and LINCOLNWELD 880M flux without preheat or postheat. With submerged arc welding heat input was 1.4 W/mm (designated as "low") and 3.9 kJ/mm (designated as "high"). Welded plates were sectioned and microhardness was measured across the plate-heat affected zone (HAZ)-weldment regions. The standard Charpy V-notch specimens were machined from the middle of the welded plate. Notches were placed in the HAZs, however, since the HAZs were very narrow, the specimens fractured in the base plate-HAZweld regions. Thus, the values for impact fracture toughness reflect the characteristics of this region.

A variety of techniques were used to characterize the microstructures of the alloys. Both grain size measurements and characterization of ferrite transformation products were carried out by optical metallography. Conventional transmission electron microscopy (CTEM) and analytical electron microscopy (AEM) techniques were employed to investigate the substructure of the alloys, and the structure and the composition of the precipitates.

Results and Discussion

The mechanical properties of the steel plates produced at Oregon Steel Mills are summarized in TABLE 2. It is evident that steel is very ductile and exceeds the 540 Mpa (78 Ksi) yield for all thicknesses investigated. FIGURE 1 shows the yield stress dependence on the plate thickness. Since cooling rate depends on the thickness of the plate, it is evident that lower cooling rate leads to lower yield strength. FIGURE 2 shows the yield/UTS ratio as a function of plate thickness; this ratio shows a U pattern with average is 0.9.

TABLE 2. Mechanical Properties of Hot Rolled and Air Cooled NUCu-Oregon Steel

PLATE #	THICKNESS, MM (INCH)	s_{YIELD}	UTS, Mpa (KSI)	ELONGATION, %
A1	12.7 (0.5)	602 (87)	623 (90)	27
A2	12.7 (0.5)	623 (90)	658 (95)	28
B1	15.9 (0.625)	595 (86)	685 (99)	25
B2	15.9 (0.625)	582 (84)	665 (96)	26
C1	19.0 (0.75)	609 (88)	727 (105)	25
C2	19.0 (0.75)	588 (85)	678 (98)	26
D1	25.4 (1.0)	561 (81)	609 (88)	26
D2	25.4 (1.0)	540 (78)	616 (89)	32

The impact fracture toughness values of the 12.7, 15.9 and 25.4-mm-thick plates were very good (TABLE 3). However, the impact fracture toughness of the 19.0-mm-thick plate was lower than that of other plates. As microstructural investigation, described later, indicates the microstructure in this plate is different from that in the other plates. This was assumed to have resulted from plate overheating during hot rolling. Indeed, as our investigation suggested, conforming to our studies on the laboratory heats, the impact fracture toughness of steel is reduced if the steel is heated at 1250°C for 30 minutes (FIGURE 3). However, the exceptionally high fracture toughness of the steel is easily restored by re-heating at lower temperatures and air cooling. For example, reheating of the specimens made from plate "B2" and plate "C1" at 950° for 30 minutes and air cooling dramatically improved fracture toughness (TABLE 4), however, it also resulted in reduction of yield stress to approximately 485 Mpa (70 Ksi). Therefore, tests were performed to determine the optimum reheating temperature that gives the best combination of strength and fracture toughness. To do that, tensile and Charpy specimens were first heated at 1250°C for 30 minutes and air cooled. As expected, the room-temperature impact fracture toughness of the steel after this heat-treatment dropped to 34 J (25 ft-lb). As Figure 4 indicates, reheating of steel to different temperatures for 30 minutes followed by air cooling affected the fracture toughness as well as the strength. The best combination of these properties was obtained at approximately 1050°C; room temperature impact fracture toughness exceeded 360 J while the yield strength was more than 530 MPa. Thus, NUCu steel has excellent strength-ductility-fracture toughness values if the final hot-rolling reheat temperature does not exceed 1150 °C.

TABLE 3. Charpy Impact Fracture Toughness of Hot Rolled and Air Cooled NUCu-Oregon Steel

PLATE No.	THICKNESS, MM (INCH)	IMPACT FRACTURE TOUGHNESS, J (FT-LBS) AT TESTING TEMPERATURE, °C (°F)					
		24 (75)	-12 (10)	-23 (-10)	-32 (-25)	-40 (-40)	-62 (-80)
A1	12.7 (0.5)	303 (222)	246 (180)			221 (162)	180 (132)
A2	12.7 (0.5)	276 (202)	>361 (>264)			264 (193)	194 (142)
B1	15.9 (0.625)	154 (113)	86 (63)			7 (5)	7 (5)
B2	15.9 (0.625)	198 (145)	172 (126)			14 (10)	5 (4)
C1	19.0 (0.75)	78 (57)	11 (8)				
C2	19.0 (0.75)	185 (135)	82 (60)	19 (14)	19 (14)		
D1	25.4 (1.0)	>361 (>264)	>361 (264)			30 (22)	7 (5)
D2	25.4 (1.0)	>361 (>264)		209 (153)	185 (135)	150 (110)	

The microstructures of the as-received plates that have good fracture toughness essentially consist of fully recrystallized equiaxed ferrite grains (FIGURE 4a). Occasionally a few pearlite colonies are also observed. The average grain size in the as-received alloys is 8.51lm (mean linear intercept). As our study indicates, the nature of the ferrite transformation product is a strong function of austenitizing temperature and subsequent cooling rate. Up to an austenitizing temperature of 1050°C, the transformed ferrite grains are essentially equiaxed and independent of cooling rate. In the temperature range of 1050 to 1150°C followed by air cooling, a mixture of equiaxed and acicular ferrite grains is observed, however they are predominantly equiaxed. At austenitizing temperature 1250°C or above, only Widmanstaten ferrite is observed (FIGURE 4b). At this temperature a dramatic austenite grain size increase is observed also. This happens probably due to dissolution at such high temperatures of very fine NbC precipitates (7-40nm) that provide very efficient grain-boundary pinning. Extraction replicas examined in TEM showed the presence of very fine NbC precipitates. The composition of the particles were confirmed by EDS

X-ray microanalysis in the AEM while the crystal structure was confirmed by electron diffraction. Thin foil examination of the as-received alloys revealed the presence of very fine scale (< 10nm) coherent metastable BCC Cu-precipitates. Optical microscopy of as-received 19.0-mm-thick plate (FIGURE 4c), that had low impact fracture toughness, demonstrates predominantly equiaxed and Widmanstaten ferrite. This microstructure indicates that this plate was hot-rolled at temperatures higher than that for plates with higher fracture toughness. Reheating this plate at 950°C for 30 minutes lead to recrystallized equiaxed ferrite grains (FIGURE 4d) and good impact fracture toughness.

TABLE 4. Charpy Impact Fracture Toughness of NUCu-Oregon Steel Normalized at 950 °C or 30 Minutes

PLATE No.	**IMPACT FRACTURE TOUGHNESS, J (FT-LBS) AT TESTING TEMPERATURES, °C (°F):**					
	24 (75)	**-12 (10)**	**-23 (-10)**	**-32 (-25)**	**-40 (-40)**	**-62 (-80)**
B2	198 (145)		172 (126)			14 (10)
B2-N*	>361 (>264)	>361 (>264)	>361 (>264)	238 (174)	>361 (>264)	260 (190)
C1	78 (57)		11 (8)			
C1-N*	>361 (>264)		>361 (>264)		202 (148)	77 (56)

*Specimens cut from plates B2 and C1 normalized at 950°C for 30 minutes and air cooled

The 15.9-mm-thick plates, produced at Oregon Steel Mill were welded manually and by automatic submerged arc process without pre- or post-heating. The hardness of the HAZ was slightly lower than that of the base plate as demonstrated, for example, in FIGURE 5 for plate welded with "low" heat input. The grain size in the HAZ was smaller than that in the base plate. The plate-HAZ-weld region had an excellent fracture toughness (FIGURE 6); even at -40 °C the Charpy values were high 138 J (manual), 187 J (automatic low heat input) and 52 J (automatic high heat input).

Summary

This research has shown that Grade 70 construction steel can be produced without a quench and temper or accelerated cooling from hot-rolling if the Cu content in the steel is sufficiently high. Coherent very fine bcc Cu precipitates form on air cooling providing strengthening to at least 485 MPa (70 Ksi). The yield strength decreases with plate thickness from 610 MPa for 12.7-mm-thick plate to 550 Mpa for 25.4-mm-thick plate. Investigation of 50-mm-thick plate is underway.

While the fracture toughness of the steel is excellent when hot-rolling temperature does not exceed 1150°C, overheating to l250°C causes degradation in fracture toughness. This is related to growth of austenite grains and appearance of some Widmanstaten ferrite. Normalizing at 1050°C restores the impact fracture toughness to above 350 J without impairing the yield strength.

No brittle heat-affected zone was formed during manual or automatic submerged arc welding without pre-heating or post-heating. The fracture toughnesses in the plate and in the heat-affected zone were excellent. While the Cu in the HAZ dissolves where the temperature exceeds the solvus, it reprecipitates on cooling. Thus there is little degradation of fracture toughness or little change in hardness in the HAZ.

Acknowledgments

Support by Infrastructure Technology Institute of Northwestern University is acknowledged. The commercial heat of steel was produced by Oregon Steel Mills, Inc., Portland, Oregon. Welding was performed by D. Hogan at welding facility of BIRL, Industrial Research Laboratory, Northwestern University directed by Dr. V. Malin.

Notes

1. Northwestern University
   Department of Materials Science and Engineering
   Evanston, IL 60208
2. Inland Steel Company, Research Laboratories
   3001 E Columbus Dr.
   East Chicago, IN 46312

Last modified: 05/22/98

FIGURE 1

Figure 1. Effect of Plate Thickness on Yield Strength of NUCu-Oregon Steel.

FIGURE 2

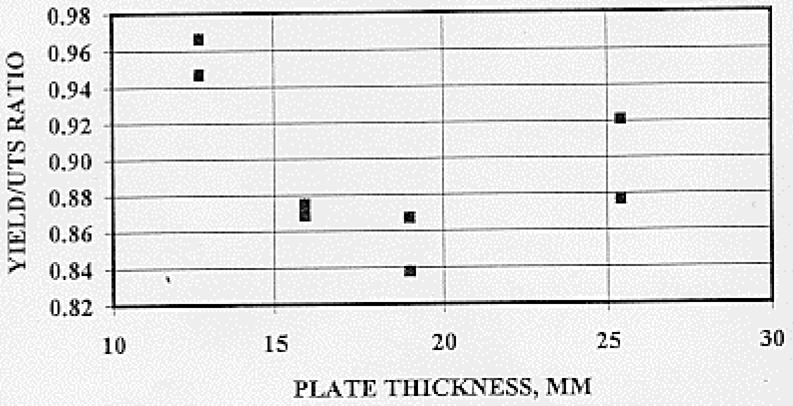

Figure 2. Effect of Plate Thickness on Yield/Ultimate Tensile Strength Ratio of NUCu-Oregon Steel.

FIGURE 3

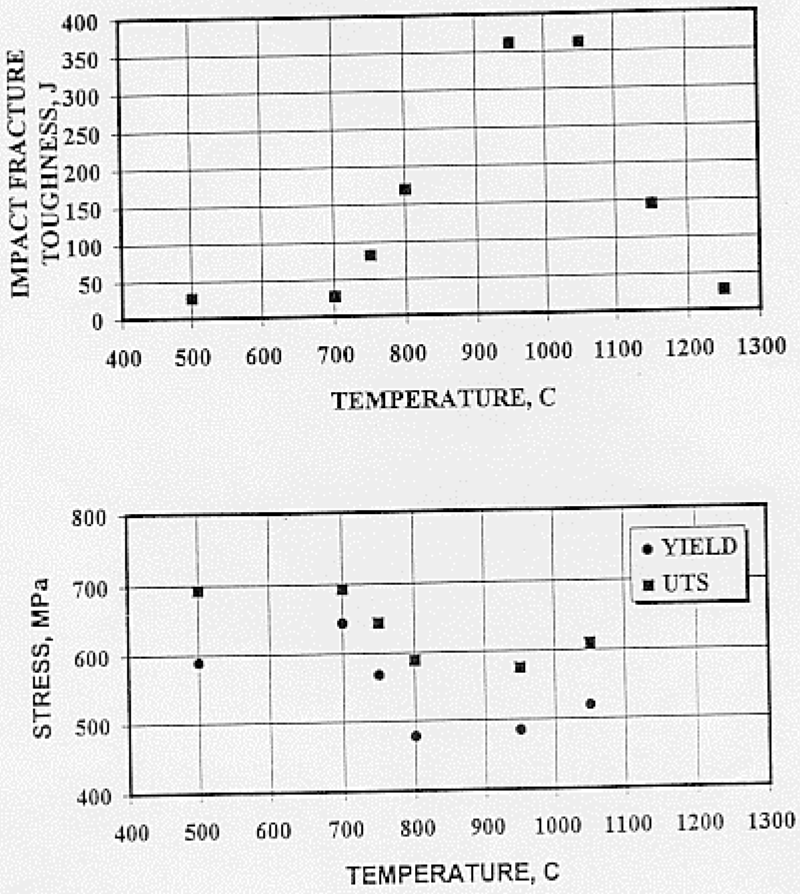

Figure 3. Effect of Reheating Temperature (30-min.) on Impact Fracture Toughness and Strength of NUCu-Oregon Steel. Specimens initially heated 30 minutes at 1250 °C and air cooled. Specimens air cooled from reheat temperature.

FIGURE 4A

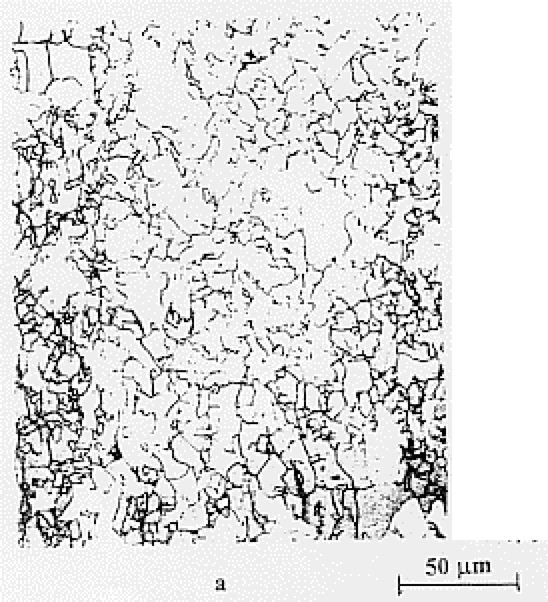

FIGURE 4B

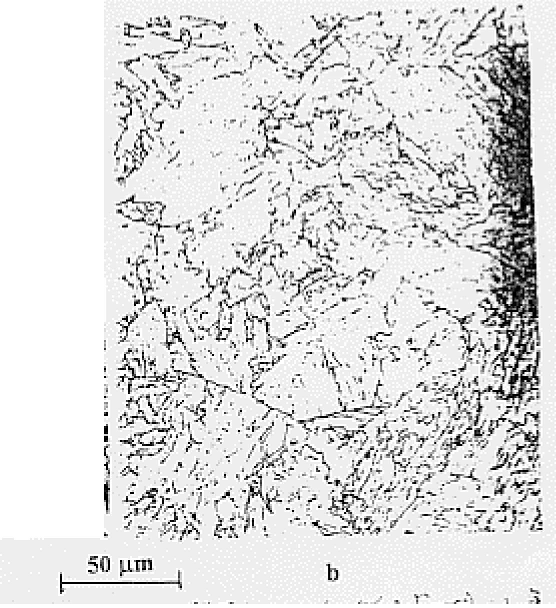

FIGURE 4C

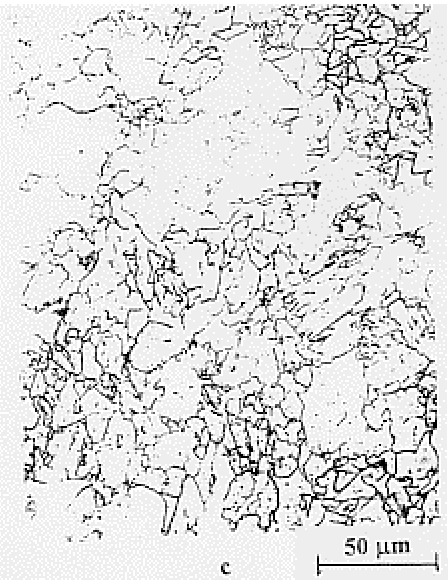

Figure 4. Microstructure of NUCu-Oregon Steel. a - plate A2 as-recieved; b - plate A2 heated at 1250°C for 30 min.; c - plate C1 as-recieved; d - plate C1 heated at 950°C for 30 min.

FIGURE 4D

Figure 4. Microstructure of NUCu-Oregon Steel. a - plate A2 as-recieved; b - plate A2 heated at 1250°C for 30 min.; c - plate C1 as-recieved; d - plate C1 heated at 950°C for 30 min.

FIGURE 5

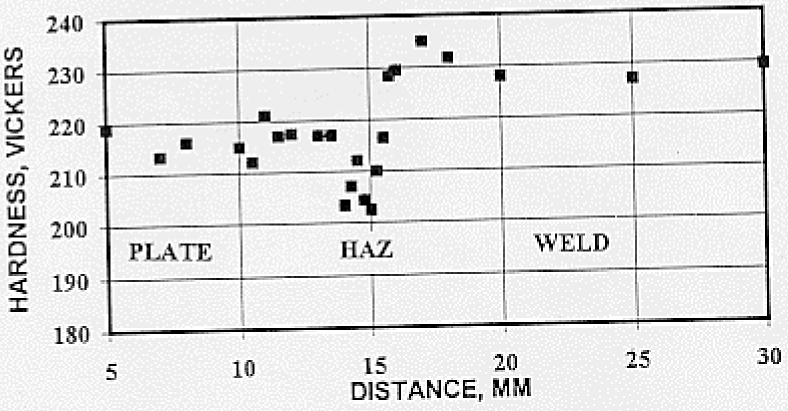

Figure 5. Microhardness Profile in NUCu-Oregon Steel Welded by Submerged Arc Process ("Low" Heat Input)

FIGURE 6

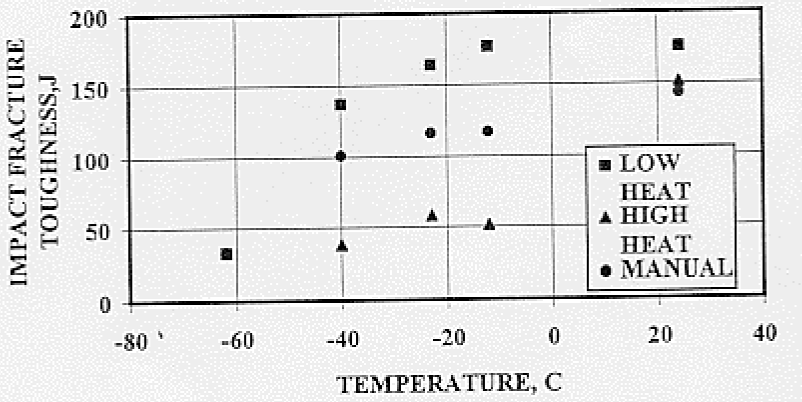

Figure 6. Charpy V-Notch Impact Fracture Toughness of Plate-HAZ-weld regions in Welded Plates.