Commercialization of NuCu Steel

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PROBLEM

For many decades, bridges have been fabricated from plain carbon steels that have yield strengths between 35 ksi and 50 ksi. In addition to high cost for materials, the fabrication cost was high due to difficulties in welding. The bridges had numerous welding cracks that in combination with low fracture toughness of the steel at low temperature led to catastrophic failures. Therefore, in the early 1990 the FHWA and the Navy identified a need for a high performance weatherable structural steel that would have a 70 Ksi yield strength (compared to 50 Ksi yield as in the micro-alloyed steels in common use). Lower carbon content for improved welding and high fracture energy at cryogenic temperatures was desired for this steel. Under the auspices of a FHWA/Navy/ AISI Steering Committee new steel designated ASTM HPS 70W was developed. This steel is martensitic and therefore requires rapid cooling followed by tempering or complex thermomechanical processing. Thermomechanical processing is available only in a small number of steel companies in US. Also, these processing conditions increase cost of the steel. In addition, when welded the steel looses some of its toughness in heat-affected zone.

At Northwestern several years after the development described above began, a different approach was taken to meet the 70 Ksi yield target steel. Our approach was to combine copper precipitation hardening and grain refinement by niobium carbides. NUCu 70W steel that is air-cooled after hot rolling resulted. If needed an additional strengthening is achieved by a low-temperature-aging heat-treatment. The steel has a number of advantages over the ASTM HPS 70W. The processing is simpler because quenching or complex thermomechanical processing are not required, therefore any steel mill can produce steel. It has the lowest equivalent carbon content of any other construction steels and, therefore, has much better weldability without pre-heat or post-heat. The steel has a remarkably high fracture energy at cryogenic temperatures. It has substantially better weathering resistance than HPS 70W steel or other weathering steels.

APPROACH

The objectives of the project were:

(a) Develop a high performance (tough, strong, improved weldability and weatherability), less expensive that presently used construction steel;

(b) To market the steel for infrastructure application.

To achieve the first objective the carbon content in the steel was lowered. The steel derived strength by copper precipitation hardening, which occurs during air-cooling. The alloying for hardenability was not required, therefore chromium and molybdenum were omitted. Ni was added to prevent hot-shortness during hot rolling. Nb and Ti were added to control grain size during hot rolling and welding. Because of simplified processing and lean composition the resulting steel is lower in cost than ASTM 709 HPS70, HSLA 80 or ASTM A710 steels.

To achieve the second objective, we worked with steel producers, steel consumers, American Iron and Steel Institute/Federal Highway Administration/ US Navy Steering Committee on High Performance Steel Development, Government Agencies (IDOT, OhioDOT), etc. We published papers and reported results of steel development at Conferences and Symposia. The steel was included into ASTM A710 Standard for Construction Steels.

METHODOLOGY

The initial development of the steel (chemical composition and processing) was done with nine laboratory heats that were produced at Inland Steel Company and US Steel Research and Technology Center. Then, two commercial 80,000-kg heats were produced at Oregon Steel Mills (OSM) to investigate the steel production under industrial conditions and for use for bridge renovation. Also, slabs previously cast at OSM were hot-rolled at U.S.Steel Gary Works and then further processed at North Star Steel Company.

The steel was already used for rehabilitation of a bridge in Illinois and is planned for another bridge construction in 2003-2004 construction seasons. To facilitate further commercialization of the steel, the 70-ksi-yield steel was included into ASTM A710 Standard. Also, the steel manufacturers (US Steel Co, OSM and North Star Steel Co.), and steel consumers consider steel application for other than infrastructure application.

FINDINGS

Mechanical and Fracture Properties

As already mentioned, a numerous heats of steel were produced in laboratory and under industrial conditions. The steel composition ranges are given in the Table 1. Carbon was kept under 0.1% to give excellent weldability. To achieve high strength the Cu concentration was between 1.3 and 1.5%. This amount of Cu significantly improved corrosion resistance of the steel. Mn and Si were added in concentrations common for steel making. Ni was added up to 0.9% to eliminate hot-shortness common for Cu-bearing steels. Nb was varied from 0.03 to 0.06. Since Nb might lead to cracking during continuous casting of the steel the effect of lower Nb concentration on properties of steel also investigated; there was no visible increase in grain size and no reduction in strength.

Ti concentration significantly affected the mechanical and fracture properties of the steel. At higher Ti concentration the yield strength of the steel dropped to 60 Ksi while low-temperature fracture toughness increased dramatically. This steel could not be fractured in Charpy machine at temperature down to –110^{o}F.

During our experimental work we found that reheating temperature before hot-rolling affects dramatically the mechanical and fracture properties of the steel. The impact fracture toughness of steel is reduced if the steel is heated at temperatures over1150^{o}C before hot-rolling. However, the exceptionally high fracture toughness of the steel was easily restored by normalizing steel in the 900 to1000^{o}C temperature range and air-cooling. The reduction of fracture toughness due to overheating was related to growth of austenite grains and formation of Widmanstaten ferrite plates that are very brittle.

TABLE 1. COMPOSITION OF STEELS (WT.%)

Element	Concentration, wt.%
C	0.03-0.08
Cu	1.3-1.5
Ni	0.45-0.90
Mn	0.45-0.60
Si	0.4-0.8
Nb	0.03-0.06
Ti	0-0.1

TABLE 2. MECHANICAL PROPERTIES OF STEELS

	Yield, ksi	UTS, ksi	Elongation, %
Ti < 0.03%	70-91	80-105	25-27
Ti = 0.1%	60	80	27

TABLE 3. FRACTURE PROPERTIES OF STEELS

Temperature, ^{o}F	Charpy Impact Energy Absorption (ft-lbs.)	
	Low Ti Steel	High Ti Steel
75	>264	>264
10	>264	>264
-40	168	>264
-80	10	>264
-110		>264

Welding of the Steel

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. Plates of NUCu steel 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 36 kJ/in (designated as “low”), 69 kJ/in (designated as “medium”) and 99 kJ/in (designated as “high”). Standard Charpy V-notch specimens were machined from the middle of the welded plates. Notches were placed in the HAZs, however, since the HAZs were very narrow, the fracture surface included the base plate, HAZ and weld regions. The plate-HAZ-weld region had excellent fracture toughness (Figure 5) even with “high” heat input; even at -40 ^{O}C the Charpy values were high: 101 ft-lb (manual), 137 ft-lb (automatic “low” heat input) and 38 ft-lb (automatic “high” heat input).

Duplicate G-BOP tests were conducted at the U.S. Steel Research and Technology Center using a heat input of 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, 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 60 KJ/in. In fracture tests at -30°C(-22°F) the average Charpy absorbed impact energy was 91 ft-lb. The requirement by American Welding Society Standard is 25 ft-lb at this temperature.

Weathering/Corrosion Characteristics of the Steel

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, the weight loss of NUCu steel was compared to that for A36 steel and other weathering steels. Townsend's results are summarized in Figure 1. It is obvious that Northwestern's steel performs best among all steels tested. The thickness loss of A36 steel was more than twice greater than that of NUCu steel. The thickness losses of A588 weathering and HPS70W A709 steels were almost twice larger than that of NUCu steel.

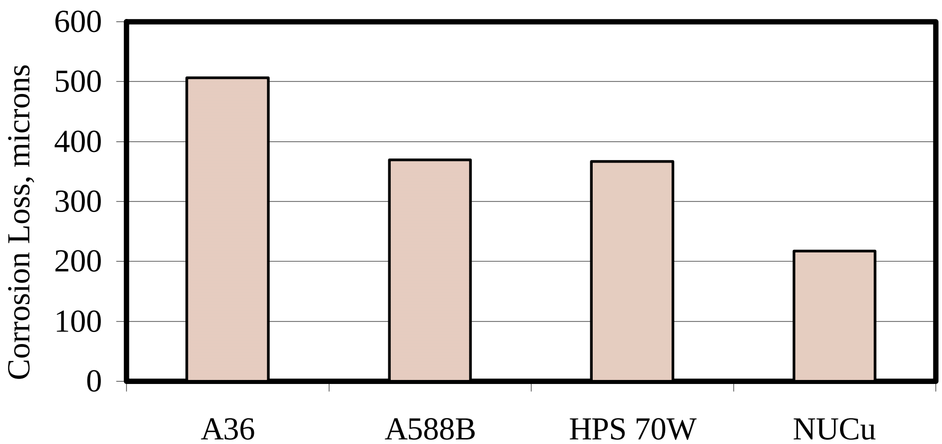

Figure 1. Corrosion loss in accelerated test conducted by Bethlehem

At the present time NUCu steel together with a number of plain carbon and weathering steels are being exposed at different corrosion sites around the USA to establish the long time weathering resistance but not enough time has elapsed to reach any firm conclusions.

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^{o}C for 3 weeks. Results of the tests are shown in the Figure 2. The widths of the corroded regions adjacent to the scratches are compared to the weight loss reported by Townsend in Figure 3. 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.

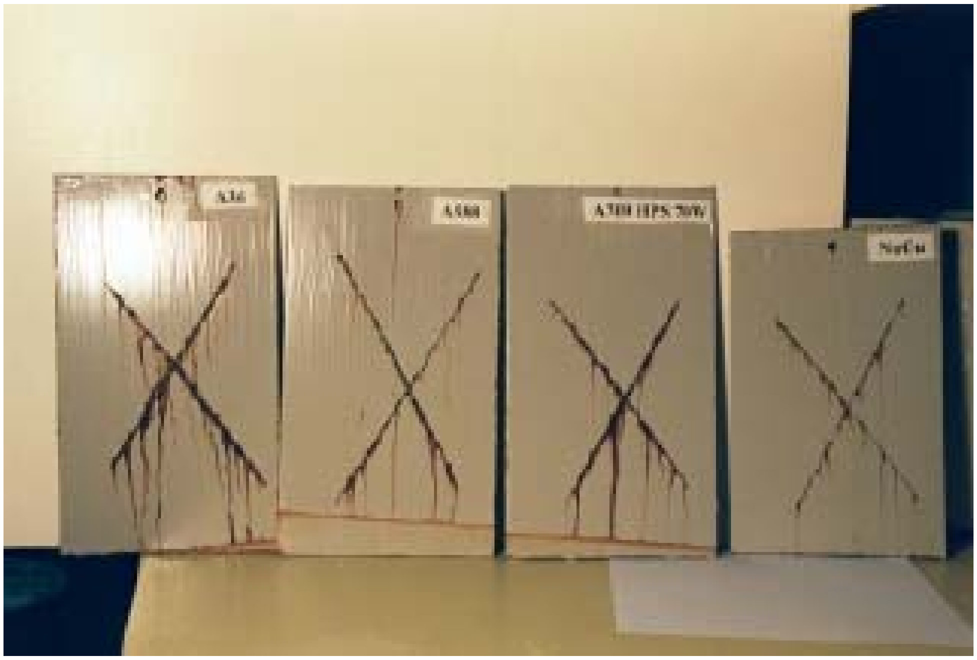

Figure 2. Painted Steel Panels after 3 Weeks, 35°C Exposure in Salt-Fog Chamber (A36; A588; ASTM HPS70W; NUCu (ASTM A710 Grade B) steels)

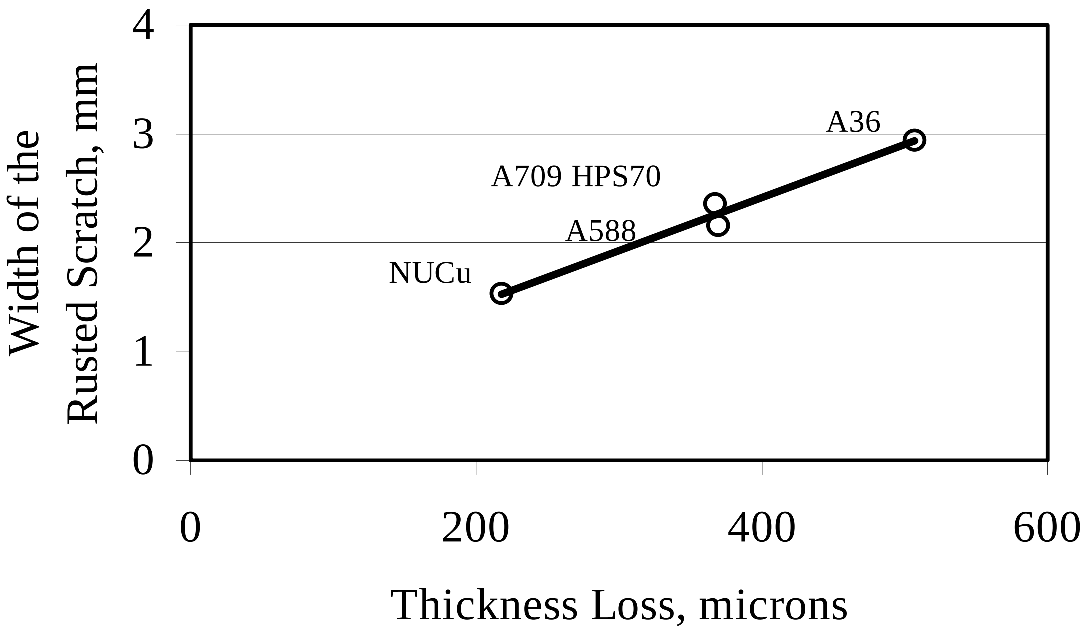

Figure 3. Comparison of the width of the rusted region on the salt sprayed scratched painted steel panels with the thickness loss of the bare steel panels in SAE J2334 tests.

Retrofitting of I-55/I-70 Poplar St. Bridge with NUCu 70W Steel

In 2000-2001, 40 tons of one-inch-thick plates of NUCu 70W steel were used in the retrofit of the I-55/I-64/U.S.-40 Poplar Street Bridge complex over the Mississippi River in St. Clare County, IL near St. Louis. This bridge, located near the Madrid fault, had a cracked member. High strength steel was required because of weight limitations and high fracture toughness was required because of seismic considerations. The steel was cast and rolled by Oregon Steel Mills, Portland Oregon. We actively participated in this project. The steel composition and processing were discussed with IDOT and Oregon Steel Mills. We were involved with bridge fabricator during fabrication. For this application (seismic considerations) the NUCu 70W steel was normalized and aged after rolling. As measured by Oregon Steel Mills and Missouri Fabricators, the yield strength was 75 Ksi and the Charpy fracture energy at -10^{o}F was 95 ft-lbs. The retrofit for this bridge was designed by Wiss, Janney, Elstner & Associates, fabricated by Missouri Fabricators and installed by St Louis Bridge Co. Figure 4 is a photograph of this bridge with the attached steel plates.

Figure 4. Photograph of the retrofitted I-55/I-64/U.S.-40 Poplar Street Bridge complex over the Mississippi River in St. Clare County, IL near St. Louis (NUCu Steel is painted in darker green)

SUMMARY/RECOMMENDATIONS

Copper-precipitation-hardened, high-performance weathering steel is produced without quench&temper or termo-mechanical controlled processing. The fracture toughness of the steel is excellent. Steel can be easily welded without pre- or post-heating. Fracture toughness of the steel is excellent. Weathering and corrosion properties are better than that of any other available construction steel. Due to simple processing the steel can be produced at lower cost than other high-performance steels by any steel producer.

The steel is an excellent candidate for infrastructure applications such as bridges, posts, signs, railings, etc.